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THE FABRICATION OF CERAMIC MOEBIUS RINGS AND THE EVALUATION OF THESE RINGS WHEN USED AS PACKING IN THE ABSORPTION OF AMMONIA FROM AIR WITH WATER

A THESIS

Presented to

The Faculty of the Graduate Division

by

Zenon Redkevitch

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy in the School of Chemical Engineering

Georgia Institute of Technology

February, 1964

THE FABRICATION OF CERAMIC MOEBIUS RINGS AND THE EVALUATION OF THESE RINGS WHEN USED AS PACKING IN THE ABSORPTION OF AMMONIA FROM AIR WITH WATER

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Date approved by Chairman: 5/29/64

ACKNOWLEDGMENT

The writer expresses thanks to Dr. H. V. Grubb for suggesting the subject matter of this thesis. His patience and kind, constructive criticism contributed immeasurably to its progress.

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SUMMARY

An important area in chemical engineering in which considerable improvement might be achieved is the design of efficient packing material. The purpose of this work was to fabricate a new tower packing of a special shape and to critically evaluate its usefulness for mass transfer operations. To carry out this purpose the work was divided into two parts: the fabrication of the packing and its subsequent evaluation.

The shape of the packing chosen for this work was the moebius ring. It appeared that such a configuration met most of the requirements of good packing; namely, unsymmetrical shape, ability of inducing turbulence and wetting of the surface of the packing, and large free volume.

For simplicity the dimensions of the moebius ring in this work were chosen as one-half inch high, and one-half inch in effective diameter. To fabricate these rings it was determined that the Ram process would be the least time-consuming. This process is the mechanical hydraulic plastic pressing of ceramic shapes by means of gypsum cement dies. Three types of cement dies were required. These were the Master Die Members, the Master Die Impressions, and the Working Die Members. To start the fabrication of ceramic moebius rings, a plastic model of the moebius ring was fabricated. Using the techniques similar to block and case work in setting up casting molds, the Master Die Members were prepared from the plastic model. For these dies a number one plaster was used

with a plaster to water ratio of ten to seven. The Master Die Impressions were cast from the Master Die Members using B-11 Hydrocal, a hard gypsum cement. The cement to water ratio in this case was two to one. The final set of dies was then prepared. The cement used for the preparation of these Working Die Members was Ceramical with a cement to water ratio of five to two. The Working Die Members were then used to prepare a quantity of ceramic moebius rings.

The rings were used as a packing in a column. While allowing water to flow down through the column over the rings, air was pumped into the bottom of the column and allowed to rise up through it. For various water and air rates the corresponding pressure drops across the packing were determined for this system. Using the same column and operating at similar conditions, measured quantities of ammonia gas were injected into the incoming air stream. By analyzing the ammonia composition of the water effluent at the various operating conditions, and applying the absorption equations, the number of transfer units, the heights of overall transfer units, and the absorption coefficients were evaluated for this system. These results were then compared with values reported in the literature for such packing as Raschig rings, Berl saddles, and Intalox saddles.

The results of this work showed that a tower packed with one-half inch ceramic moebius rings contained 9,000 rings per cubic foot. The rings presented a surface area of 104 square feet per cubic foot and a void space of 63 per cent. For this tower the flooding region occurred at a pressure drop from 4.6 to 4.8 inches of water per foot of packing.

Over this range the water flow varied from 10,945 to 4,900 pounds per hour per square foot and the air flow varied from 380 to 640 pounds per hour per square foot. The pressure drop at flooding was about 34 per cent higher than across a tower packed with 1/2-in. ceramic Raschig rings. Below the flooding region the pressure drop across the moebius rings was proportional to the 1.9 power of the gas flow. The proportionality decreased to the 1.6 power of the gas flow as the constant water flow parameter increased from 1,225 to 10,945 pounds per hour per square foot.

When operating at water rates from 3,600 to 5,350 pounds per hour per square foot, and at air rates from 200 to 500 pounds per hour per square foot, the pressure drop across the moebius rings was 25 per cent more to 45 per cent less, 12 to 17 per cent more, and 11 to 14 per cent more than the pressure drop across a tower packed with 1/2-in. ceramic Raschig rings, Berl saddles, and Intalox saddles, respectively.

A column packed with 3/4-in. or 1-in. Raschig rings, Berl saddles, or Intalox saddles, showed pressure drops of 10 to 20 times lower than for a column packed with 1/2-in. moebius rings.

When used as a packing in the absorption of ammonia from air with water, the height of the overall transfer unit, H_{OG}, for the moebius rings decreased with increased water rates, and increased slowly with increased gas flow up to the flooding region. Above flooding, H_{OG} rapidly decreased. Below the flooding region and at low water rates, Raschig rings and Intalox saddles ranging in size from 3/8-in. to 1-in. gave H_{OG} values which were only slightly higher than the H_{OG}'s of the

moebius rings. At higher water flows the H_{OG}'s of the standard packings were as much as 85 per cent higher than the H_{OG}'s of moebius rings.

At constant water flows the K_Ga's for moebius rings were proportional to a power of the air flow. This power increased from 0.43 to 0.79 as the water flow parameter increased from 1,558 to 6,232 pounds per hour per square foot. The K_Ga's of the standard 1/2-in. packing and the moebius ring were equal within a 10 per cent variation for the low water flow. For a water flow of 4,500 pounds per hour per square foot the K_Ga's of the standard 1/2-in. packing were 20 to 40 per cent lower than the K_Ga's of the moebius rings.

Although the absorption coefficients for moebius rings were equal to or better than the reported K_Ga's of the investigated standard packings, the pressure drops across the moebius rings were considerably higher than anticipated. The 1/2-in. moebius ring apparently allowed a large liquid hold-up which hindered gas flow through the column. A moebius ring with a ratio of diameter to height of more than one could conceivably decrease the liquid hold-up.

CHAPTER I

INTRODUCTION

General

The efficiency of many of the unit operations of chemical engineering depends in part upon the surface contact between the phases. There are numerous methods of effecting such contact. For simplicity, let us consider only one of the unit operations as practiced in industry.

Gas absorption is one of the major unit operations based on interphase mass transfer. This unit operation involves the removal of one or more selected components from a mixture of gases by dissolution in a liquid. Thus, the recovery of ammonia may be effected from an ammonia-air mixture, by the absorption of ammonia in water. Similarly, an acetone-air mixture can be passed through water with the result that the acetone dissolves while the air passes out. A very important factor in absorption is the amount of contact surface available for interphase mass transfer. In industry, to obtain large surface contact, gas absorption is carried out in one of three types of towers or columns. These are the plate, spray, and packed towers (1).

In bubble-cap towers, the liquid and gas are contacted on trays or plates. The vapor or gas rises through openings in the trays into bubble caps. Each bubble cap contains many openings through which the gas may bubble into the liquid. The liquid, in turn, flows downward from tray to tray through downspouts, crossing first one plate and then the next

one below. Much of the interphase transfer occurs as the gas bubbles are formed as they rise through the agitated liquid. A small amount of transfer may also take place above the liquid surface. The practical advantage of this type of equipment is that the gas stream may be uniformly dispersed through all the liquid (2). Towers made up with plates of sieve trays operate on the same principle. Channelling is avoided since stagnant zones are easily eliminated (2).

In operation, the interfacial surface between phases is made as large as is practically possible. This is done by considering the individual effects. Thus, large depths of liquid on the trays lead to long contact time and high efficiency, and also to high pressure drops per tray. High gas velocities provide not only efficient dispersion and high vapor-liquid contact, but also excessive entrainment and high pressure drop. The surface contact available for mass transfer in plate towers is, therefore, limited by the design of the tower and the conditions of operation (3).

A second method of enhancing surface contact of gas and liquid is by means of sprays. When liquid is sprayed through a nozzle, it may be dispersed into a fine spray of drops. If this is carried out in a large empty tower into which gas is also introduced, one obtains a spray tower. During operation, the diffusional transfer takes place across the interfacial surface provided by the great number of small drops. The mechanics of such transfer in small drops is that of molecular diffusion. The larger drops are mixed internally due to frictional drag acting on the drop surface. Some disadvantages of spray towers are the high pumping cost for the liquid; the spray's tendency for entrainment

of liquid by the leaving gas; the rapid mixing of the gas; and the condensation of the spray on the walls of the tower (2).

The third and perhaps the most widely used method of providing a large interfacial area for mass transfer is the packed column. The tower consists of a vertical column filled with material of large surface area per unit volume. This material is the packing. For most operations, the liquid is introduced at the top of the tower and flows by gravity down through the packing to the bottom. It flows in thin films and in so doing exposes a large surface area (4, 5). The gas may be introduced into the tower to flow concurrently or countercurrently. One disadvantage of the packed tower is the problem of maintaining uniformity of liquid and gas flow (6). Care must be exercised to eliminate "channelling" of the liquid through the packing. In any case, the gas makes contact with the continuously changing surface of the liquid and mass transfer may occur.

There are numerous types of packing that may be used. These range from simple crushed stone to complicated shapes fabricated commercially (7). In general, there are several characteristics that are desirable in an ideal packing. In reaching a decision as to the type of packing to use in a tower, the following items might be considered (8, 9):

1. Effective surface area per cubic foot of packed tower space.

2. Free or void volume per cubic foot of packed space. This is the space unoccupied by the substance of packing material per cubic foot of packed space.

3. Free area per square foot of cross-sectional tower area. This is the area unoccupied by the substance of packing material. It is the area available for the passage of gas at the junction of adjacent tiers of packing.

4. Resistance to gas flow. This is expressed as the pressure drop required to produce a given velocity through the packing.

5. Tendency to accumulate particles of solids brought into the tower by the gases or liquids.

6. Weight of the packing per cubic foot.

7. Duration of contact between gas and liquid.

8. Stability of position as packed, or the degree of side-thrust against tower walls.

9. Durability in the presence of the fluids handled.

10. Tendency toward segregation of flowing gas in open spaces and of liquid on surface area to cause channelling. Channelling hinders the direct contact of gases and liquids.

11. Cost per square foot of effective surface area and per cubic foot of packed tower space as stacked.

There are, of course, other methods of producing surface contact. These are, however, either not too important commercially, or else modifications of those described above. For example, a sieve tray may be considered to be similar to a bubble-cap tray. A wetted wall column is actually a special case of a packed tower.

Statement of Problem

The area in which considerable improvement might be achieved

and which is quite important to the chemical engineering industry is the design of efficient packing material. The purpose of the present work was to fabricate and evaluate a specially shaped packing which might be an improvement over presently available materials. Of consideration would be the above-listed items for packing design. The major portion of this work would of necessity be the actual fabrication of the packing material. Sufficient packing would be required to determine the characteristics of this packing in actual operation. A comparison of these characteristics would be made with those of certain existing well known packings. Further, the method of fabrication would have to be one that could lend itself to commercial manufacturing methods.

The shape that was chosen for this work was quite simple. It was the moebius ring (10). Such a ring may be formed by taking a thin rectangular sheet, twisting it one-half turn, then joining the ends. Thus, a one-sided surface is obtained. A moebius ring appears to meet many of the requirements of good packing. It is not symmetrical. Therefore, it would not tend to stack in a series but would maintain randomness naturally. The twist might produce more turbulence and more wetting of the surface of the packing, and therefore yield more efficient mass transfer. Another important factor of packings is that of void space. It appeared that this type of ring would be "open" and, therefore, have a large void volume. A large void space indicates the possibility of low resistance to flow and is consequently a desirable item. All of these factors would have to be either proved or disproved. It also remained to be established that a moebius ring could be simply and cheaply fabricated.

Literature

While many different types of packings have been investigated, only those that have found use in industry will be described here.

Raschig Rings

These rings are perhaps the most widely used in industry. The ring is defined by the specification that the height shall equal its outside diameter. The wall thickness must be as thin as possible to give a high fraction of free space and low apparent density. Raschig rings may be made of porcelain, ceramic, glass, carbon, metal or other materials. A simple method of fabrication of these rings is by extrusion. Table 1 lists some characteristics of ceramic raschig rings (11).

Table 1. Ceramic Raschig Rings

Nominal Size	Approximate Number per Cubic Foot	Approximate Surface Area Square Foot/ Cubic Foot	Per Cent Free Space
3/8"	26,000	148	53
1/2"	10,700	114	53
1"	1,330	58	68
1-1/2"	380	36	68
2"	165	29	83

Berl Saddles

The Berl saddle is a saddle-shaped unit that may be formed by punch

dies. This packing may form an interlocking structure which reduces channelling and increases the area of packing that may be wetted during operation. Because it is an open packing, it is theoretically possible to wet its entire surface. Table 2 shows some characteristics of Berl saddles (12).

Table 2. Ceramic Berl Saddle Packing

Nominal Size	Approximate Number per Cubic Foot	Approximate Surface Area Square Foot/ Cubic Foot	Per Cent Free Space
1/2"	16,200	142	63
3/4"	5,000	82	66
1"	2,200	76	69
1-1/2"	580	44	75
2"	250	32	72

Intalox Saddles

Intalox saddles are very similar to Berl saddles. A difference is that the ends are made shorter to eliminate the stacking effect obtained from the Berl saddle. This means that the Intalox saddle will pack in a random manner without an excess of pattern packing. Generally, Intalox saddles have been found to give better results in packed towers than either the Raschig rings or Berl saddles. Some physical characteristics of Intalox saddles are shown in Table 3 (13).

Table 3. Ceramic Intalox Saddles

Nominal Size	Approximate Number per Cubic Foot	Approximate Surface Area Square Foot/ Cubic Foot	Per Cent Free Space
1/2"	20,700	190	78
3/4"	6,500	102	77
1"	2,385	78	77.5
1-1/2"	709	59.5	81
2"	265	36	79

Pall Rings (14)

The Pall ring is simply a modified Raschig ring in that its height is equal to the diameter. During the fabrication operation, the cylinder wall is punched to produce projections bent inward. The ring thus has more void space with the result that liquid channelling and pressure drop are decreased. There is also an increase in the wetting of the ring surface.

The Rosette (15)

The design of this packing was based on the theory that increased interstitial hold-up would result in higher efficiency of mass transfer. The shape of the packing is described as a helical torus or a multiple helix in the form of a doughnut.

Reported Data

There have been numerous papers reporting the evaluation of

various characteristics of packings. White (16) reports the pressure drops at various air and water counter current flows in columns packed with 3/8-in., 1/2-in., 5/8-in., 3/4-in., 1-in., and 1-1/4-in. stoneware Raschig rings. He shows that for water flows of 2,040, 1,490, 750 and 0 pounds per hour per square foot, 3/8-in. Raschig rings dumped in a 3-in. diameter column will develop a pressure drop of 1.0 in. of water per foot of packing at air flows of 319, 368, 427 and 680 pounds per hour per square foot, respectively. Flooding occurs at a pressure drop of about 3.5 in. of water per foot of packing height.

For 1/2-in. Raschig rings in a 3-in. diameter tower, flooding occurs at about 3.0 in. of water per foot of packing height. A pressure drop of 1.0 in. of water per foot of packing is obtained at water rates of 5,425, 2,040 and 750 pounds per hour per square foot. These liquid flows are for air flows of 430, 620 and 680 pounds per hour per square foot, respectively. The data of White generally show that with increasing packing size, (a) the pressure drop at which flooding occurs slowly decreases, and (b) for a given pressure drop and liquid flow, the gas flow slowly increases. It is further shown that the effect of using a 6-in. instead of a 3-in. diameter tower for a 1/2-in. packing is to (a) increase the flooding pressure drop, and (b) decrease the gas flow corresponding to a particular pressure drop and water flow.

Furnas and Bellinger (17) measured the pressure drops of 1-in. stoneware Berl saddles and 1-in. Raschig rings. The data were obtained from a water-air system in a 12-in. diameter tower. No flooding conditions were reported. For comparable water flows, at equal pressure drops, the Berl saddles allowed about 75 per cent more air flow.

Schoenborn and Dougherty (18) determined the pressure drops for various water and gas flows over 1/2-in. Berl saddles. Their results led to the general conclusion made by Furnas and Bellinger. Namely, that at equal pressure drops, the gas flows for specific water flows were about 75 per cent higher for Berl saddles than for similar size Raschig rings. Data of Eckert, Foote, and Huntington, in the U. S. Stoneware publication, Packed Towers (19), show the pressure drops for 1/2-in., 3/4-in., and 1-in. Raschig rings, Berl and Intalox saddles. When compared with the Raschig ring and the Berl saddle, the Intalox saddle exhibited certain advantages. These were: (1) 30 to 40 per cent lower pressure drop; (2) more free space; (3) increased flooding rates; (4) 20 to 30 per cent higher efficiency; and (5) greater surface area per cubic foot of packing.

Other data of Eckert, Foote and Huntington in the publication (19), compare the pressure drops across Raschig rings and Pall rings. It was found that Pall rings offered about 25 per cent of the resistance to flow than did Raschig rings. A. J. Teller (15) described the design and evaluation of the Rosette ring. When compared with 1-1/2-in. Raschig rings and Berl saddles, Teller's data showed that the resistance of the 3/4-in. by 2-in. polyethylene Rosette to gas flow is between the two. That is, for equal gas and water flows, the Raschig rings showed 50 per cent higher pressure drops, and the Berl saddles showed 20 per cent lower pressure drops than the Rosettes.

The study by Fellinger (20) to compare the absorption coefficients of numerous packings in an air-water-ammonia system is perhaps the most extensive and reliable published. Fellinger measured the $K_G a$'s of

different packings in the water flow range of 500 to 4,500 pounds per hour per square foot, and in the gas flow range of 200 to 1,000 pounds per hour per square foot. He used an 18-in. column, and attempted to correct for end effects. The $K_G a$'s for 3/8-in. Raschig rings varied from 8.3 to 30 pound-moles per hour-atmosphere-cubic-foot for gas flows of 200 to 700 pounds per hour per square foot at a constant water flow of 1,500 pounds per hour per square foot. At a water flow of 4,500 pounds per hour per square foot, the $K_G a$'s varied from 9.8 to 33 pound-moles per hour-atmosphere-cubic-foot for gas flows of 200 to 400 pounds per hour per square foot. Generally, the coefficients were found to increase with increasing packing size and water flows. However, the increase was not profound. For example, the $K_G a$'s of 1-in. Berl saddles measured at a constant water flow of 4,500 pounds per hour per square foot were found to be 15 to 47 pound-moles per hour-atmosphere-cubic-foot in the gas flow range of 200 to 1,000 pounds per hour per square foot. It should also be noted that the $K_G a$'s for Berl saddles were about 10 per cent higher than the $K_G a$'s found for similar size Raschig rings. Below incipient flooding the $K_G a$'s were approximately proportional to the 0.8 power of the gas flow. Above the flooding rate, however, this relationship did not hold and the $K_G a$'s increased very rapidly in the case of Raschig rings.

Fellinger's data has been reproduced many times, but is usually presented in the form of H_{OG}, the height of the overall transfer unit based on the gas phase. Data reproduced in Tower Packings and Packed Tower Design by Max Leva (21) show that below the flooding region for packings up to 1-in., the H_{OG}'s are in the range of 0.5 to 1.2 feet for

the water and gas flows mentioned above. Above the flooding point, the H_{OG}'s for Raschig rings drop very sharply.

Theory

For specific gas and liquid flows, the optimum operation of packed towers is realized when the liquid flows over all the packing at as uniform a rate as possible. Below the "loading" velocity the liquid is considered to be flowing freely over the packing; therefore uniform liquid rates may prevail. The loading velocity is indicated by a variation in the relation between the pressure drop in the packing and the gas velocity. Below this velocity, the pressure drop varies approximately as the 1.8 power of the gas velocity. The point at which the power relation increases from 1.8 to a power above 2, is the "loading velocity" as defined by White (16). Above this velocity, the liquid does not flow freely from the packing. The change in the pressure-drop variation is consequently accompanied by an increase in the liquid retention or "hold-up" of the packing. The liquid retained fills up many of the interstices of the packing and thus decreases the surface of contact between the phases.

As the liquid flow rate in the tower is still further increased, a point is reached where this large quantity of liquid can no longer flow out of the tower. At this point, the pressure drop in the column tends to increase with gas rate even more rapidly as it approaches the hydrostatic head of the liquid filling the column. Simultaneously, entrained liquid appears in the overhead gas stream, because the liquid can no longer run out the bottom of the column as fast as it is fed in. It

must, therefore, overflow at the top. The rate producing this condition is called the "flooding velocity." Above this rate, a tower cannot be effectively operated.

It is apparent that in the design of packed towers, loading and flooding play an important role. A knowledge of the pressure drop characteristics of packing is necessary when considering the power requirements and the limiting conditions for optimum mass transfer. Figure 1 (22) shows the general method for presenting pressure drop data for packing. The logarithm of the ratio of pressure drop in inches of water per foot of packing height is plotted against the logarithm of the gas rate. The data are generally obtained at several liquid rates. Both the gas and liquid rates are expressed in pounds per hour per square foot of cross-section.

Although the pressure drop characteristics of packing are important in tower design, the effectiveness of the packing in mass transfer is also extremely important.

Regardless of the type of equipment that may be used for gas absorption, the prime requirement for mass transfer is that the gas and liquid be brought into direct contact. Absorption will then take place only if the soluble substance of the gas mixture is transferred from the gas phase to the liquid phase. This occurs when the solute diffuses through the gas phase to the gas-liquid interface and then into and through the liquid phase. The diffusion process is maintained by concentration gradients in the direction of diffusion within each phase. Thus, in the gas phase, the diffusional resistance that must be overcome by the concentration gradient lies essentially within a thin

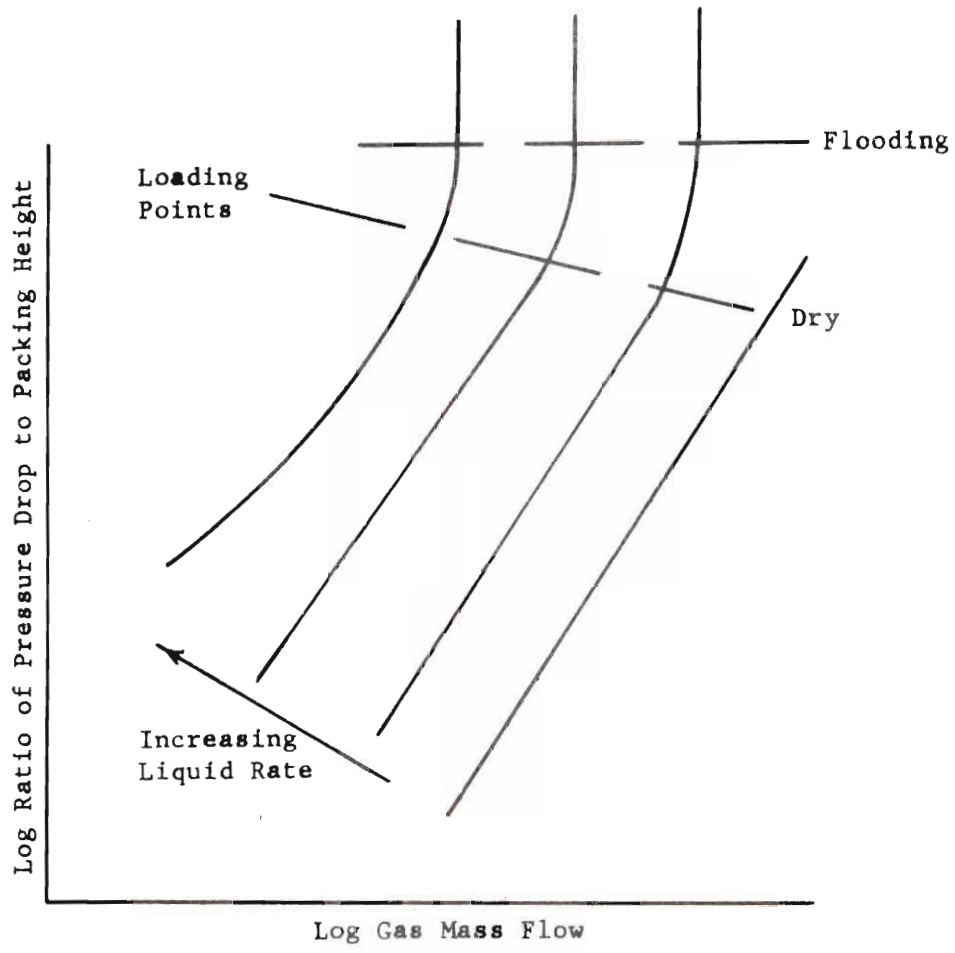


Figure 1. Pressure Drop in Irrigated Beds of Packing

laminar film at the interface between the two phases. A similar situation exists within the liquid phase. This theory was introduced by Whitman in 1923 (23).

Figure 2 is a diagrammatic representation of the conditions existing in the thin films of gas and liquid adjacent to the interface. The diagram indicates the partial pressure of the soluble gas in the gas phase. It also shows the concentration of the dissolved gas in the liquid phase. The driving force across the gas film is given by $(P_g - P_i)$ and that across the liquid film by $(C_i - C_l)$. P_g and P_i represent the partial pressures of the solute in the gas phase and interface, respectively. C_i and C_l represent the concentrations of the dissolved gas at the interface and in the liquid phase, respectively.

If,

N = rate of mass transfer through unit area of interface (lb. moles/hr.-ft.^{2}).

k_g = gas-film coefficient (lb. moles/hr.-ft.^{2}atm.).

P_g = partial pressure of dissolved gas in gas phase (atm.)

P_i = partial pressure of dissolved gas at interface (atm.)

then,

$$N = k_g (P_g - P_i)$$

defines the rate of transfer of material through the gas film. This equation, however, is not very practical since neither k_g nor P_i may

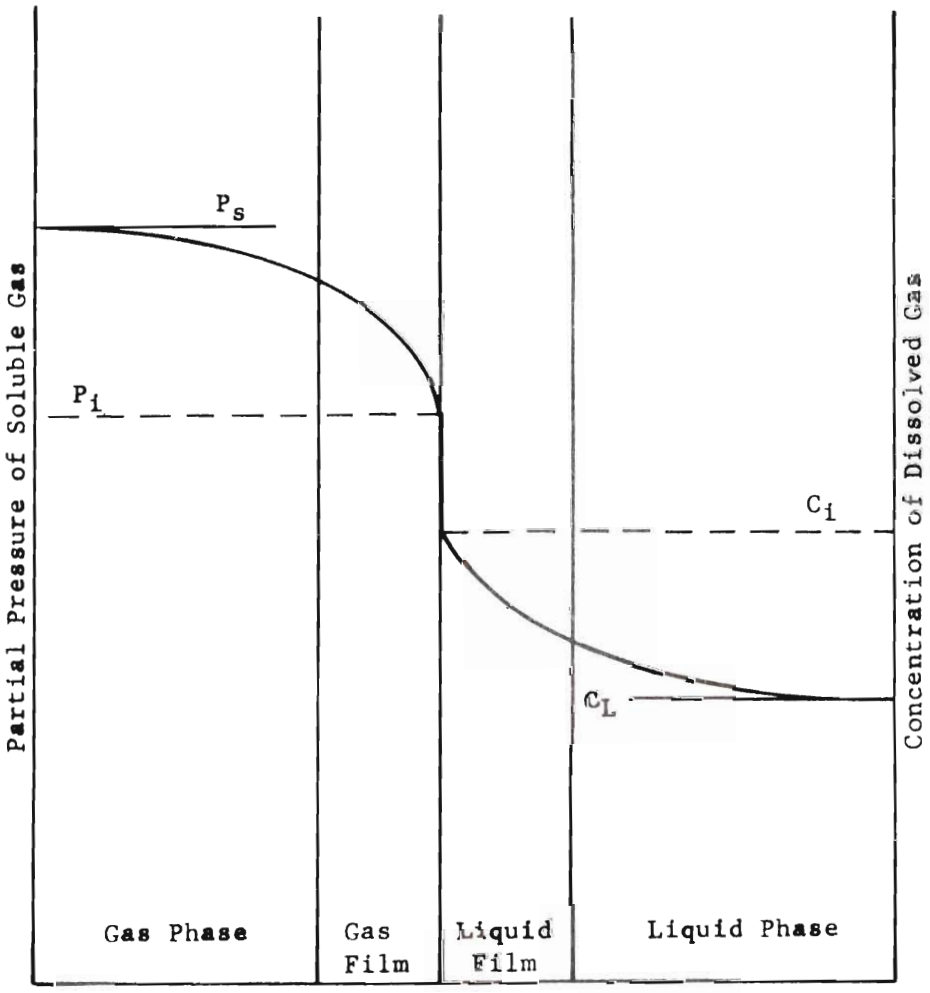


Figure 2. Principle of Two-Film Theory

be easily determined. It is, therefore, advantageous to use an overall coefficient K_G which is defined by the equation:

$$N = K_G(P_g - P_e).$$

P_e is the partial pressure of solute over a solution having the composition of the main liquid stream. If the gas is very soluble, then the resistance to mass transfer is predominatly in the gas film while the liquid film contributes very little to the overall resistance. Therefore, one may use the above equation to determine transfer of material from the gas phase to the liquid phase in this case.

Let us now consider the operation of a simple gas-liquid absorption tower. A gas phase is introduced at the bottom of the tower, rises through the column and escapes from the top. A liquid phase is introduced at the top of the tower, flows down through it over the packing and escapes from the bottom. The gas phase consists of inert gas and a solute gas. Its composition may be expressed as the ratio of moles of solute gas to moles of inert gas. The liquid phase is made up of a liquid solvent and dissolved solute gas. Its composition may similarly be expressed as the ratio of moles of solute to moles of solvent. Let us further assume that the solute gas is more than slightly soluble in the solvent.

Taking a material balance on the tower when operating at steady state conditions, combining the result with the above equation one obtains the following relationship (24).

$$Z = \int_{o}^{Z} dZ = \frac{G}{K_G a P \phi} \int_{Y_B}^{Y_T} \frac{dY}{Y - Y_e}$$

The values of Ye are obtained from the equilibrium relationship of the gas and liquid phases. If this equilibrium relationship is nearly linear then one may integrate the above equation by means of the log mean average. Therefore,

$$Z = \frac{G}{K_G a P} \cdot \frac{1}{\phi} \cdot \left[\frac{(Y_B - Y_T)}{(Y-Y_e)_B - (Y-Y_e)_T}\right] \ln \left[\frac{(Y-Y_e)_B}{(Y-Y_e)_T}\right].$$

The symbols in these equations are defined as follows:

Z = total height of packed section of tower. (ft.)

a = interfacial area per unit volume of the column. (sq.ft./cu.ft.)

K_G = overall gas-film coefficient. (lb.moles/hr.-ft.^{2}atm.)

P = average total pressure of gas phase. (atm.)

G = moles of inert gas per unit time per unit cross-section of tower. (lb.moles/hr.-sq.ft.)

Y = concentration of the solute in the gas phase. (moles of solute/mole of inert gas)

Y_e = concentration of the solute in the gas phase when the gas phase is in equilibrium with the main liquid stream. (moles of solute/mole of inert gas)

ϕ = mathematical correction term introduced for simplification. By definition (25).

$$\phi = \frac{1}{2}\left(\frac{1}{1+Y_B} + \frac{1}{1+Y_T}\right)$$

Subscripts B and T refer to the bottom and the top of the tower, respectively. It is convenient to express the height of the column as the product of the number of overall gas transfer units, N_{OG}, and the height of one transfer unit H_{OG}. Thus,

$$Z = N_{OG}\ H_{OG}$$

where

$$H_{OG} = \frac{G}{K_G a P}$$

or,

$$K_G a = \frac{G}{H_{OG} P}$$

and,

$$N_{OG} = \frac{1}{\phi} \int_{Y_B}^{Y_T} \frac{dY}{Y-Y_e}$$

$$= \frac{1}{\phi} \quad \frac{(Y_B - Y_T)}{(Y-Y_e)_B - (Y-Y_e)_T} \quad \ln \quad \frac{(Y-Y_e)_B}{(Y-Y_e)_T}$$

N_{OG} is the integrated value of the change in composition per unit driving force, and, therefore, represents the difficulty of the separation.

Proposed Approach to the Problem

It appeared that the shape of the moebius ring would lend itself to the simple methods of fabrication, such as pressing. An attempt would therefore be made to apply such a process to fabricate a sufficient quantity of moebius rings for use in evaluation studies. For ease of handling it was decided that the moebius ring should be 1/2-in. high, and 1/2-in. in effective diameter. After fabrication certain physical characteristics of the rings could be determined. Of primary interest would be the void space, the number of rings per cubic foot occupied, and the surface area per cubic foot.

The rings would then be used as packing in a column. While allowing water to flow down through the column over the rings, air would be pumped into the bottom of the column and allowed to rise up through it. For various water and air rates the corresponding pressure drops across the packing and consequently the flooding region would be determined for this system. Using the same column operating at similar conditions, known amounts of ammonia would be injected into the incoming air stream. The tower would then be operating as a gas-liquid absorption column. By analyzing the ammonia composition of the water effluent at various operating conditions and applying the absorption equations, the number

of transfer units, the heights of overall transfer units, and the absorption coefficients would be evaluated for this system.

All of these results for moebius rings would then be compared with values reported in the literature for such packing as Raschig rings, Berl saddles, and Intalox saddles.

CHAPTER II

MATERIALS, EQUIPMENT AND INSTRUMENTATION

Equipment Used for Fabrication of Moebius Rings

General

To fabricate the moebius rings to be used in this work, it was determined that the Ram process would be the least tedious. This process is a development of Ram Incorporated, in Columbus, Ohio. It is the mechanical hydraulic plastic pressing of ceramic shapes with gypsum cement dies. The details of this process are discussed more completely in the chapter on Procedures.

The Ram process requires a minimum of equipment. Any shape that can be made in a two-piece mold can be adapted to the Ram Process. Figure 3 is a photograph of the operational equipment. Here we see a press with controls for lifting and lowering, male and female dies and air controls. Figure 4 is a labelled schematic for the same setup.

The Press

The Ram Press used for this work was a six-ton C Frame Denison Press. Its use was obtained through the courtesy of Dr. Moody of the Ceramic Engineering Department. Basically, this press is very similar to a simple drill press. The difference is that the ascent and descent of the movable plate may be automatically controlled.

Air Valve

The air valve was a Hannifin (P-25) 1/4-in. IPT manual valve.

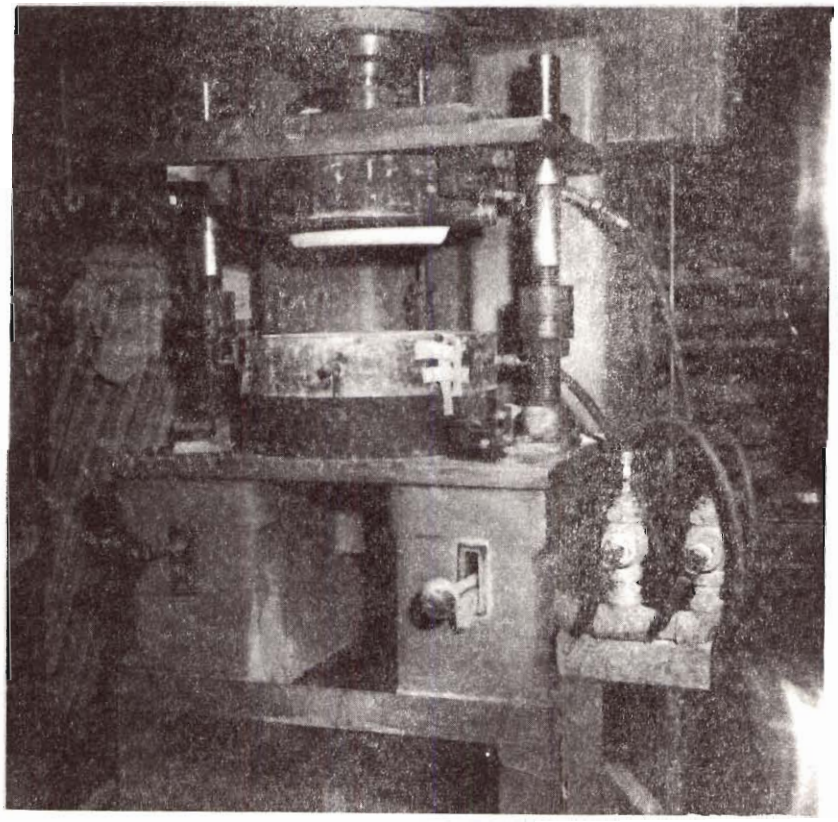


Figure 3. Photograph of Equipment for Ram Process

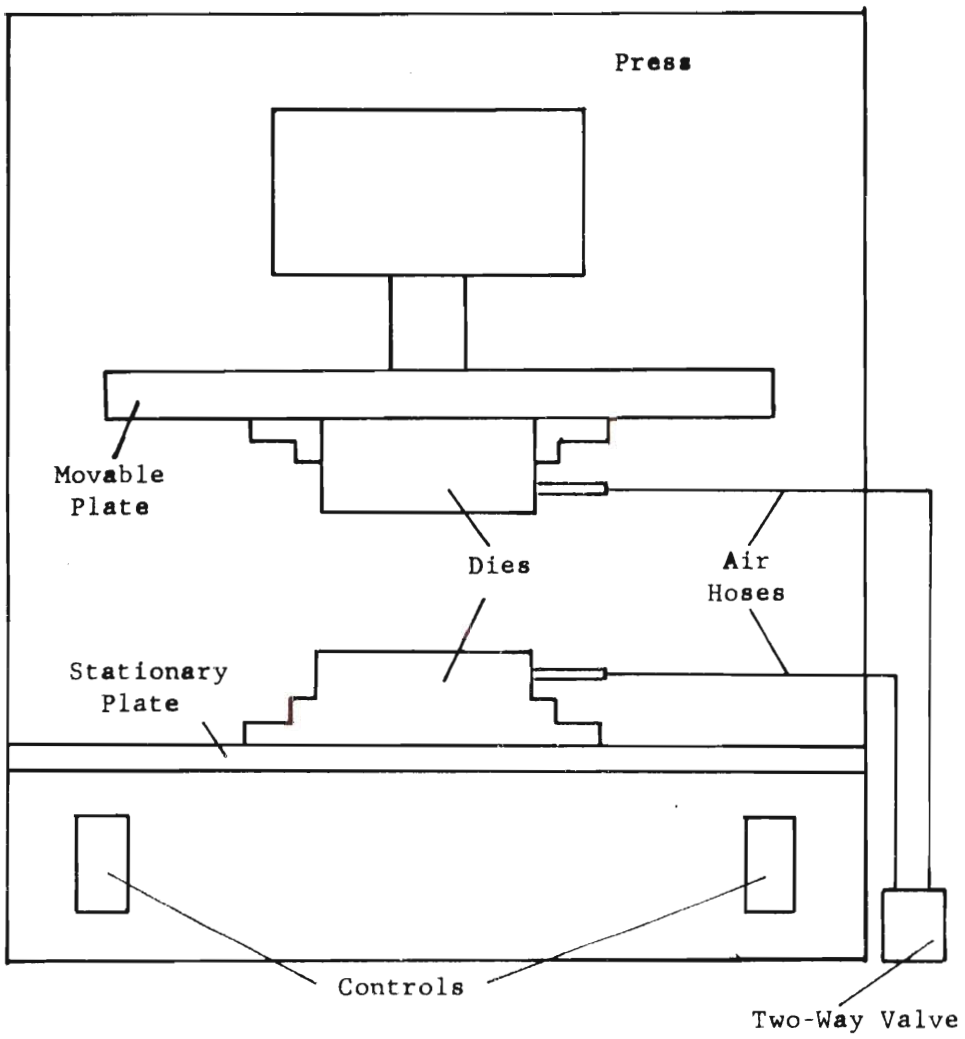


Figure 4. Ram Press and Dies

Its function was to allow air to be blown through either cement die to affect the release of the molded article from that die.

Die Cases

The die cases were made from standard 6-in. steel pipe. Three pairs of cases were made. These were simply rings cut from the pipe such that their height was 3-in. The inside surface of the rings was left rough and unpolished. The outside and top and the bottom surfaces were polished smooth. To be able to properly align or register mating die cases, the top of each ring was drilled to provide registration holes. One pair of cases was for the final working dies. This pair was equipped with hold-down clamps and nozzles for air hose fittings. Figure 5 shows a diagram of the cases.

Cement for Dies

Cements were prepared with procedures and techniques similar to block and case work in setting up casting molds. Three fabrications were required.

1. Master Die Members
2. Master Die Impression
3. Working Die Members

For the master die members, a number one plaster was used. The plaster to water ratio was ten to seven. The master die impressions are the reverse of the master die members. These were made from B-11 Hydrocal, a hard gypsum cement. A cement to water ratio of two to one was found to be adequate. The working die members were made from the master die impressions. The cement for these dies was the hard gypsum

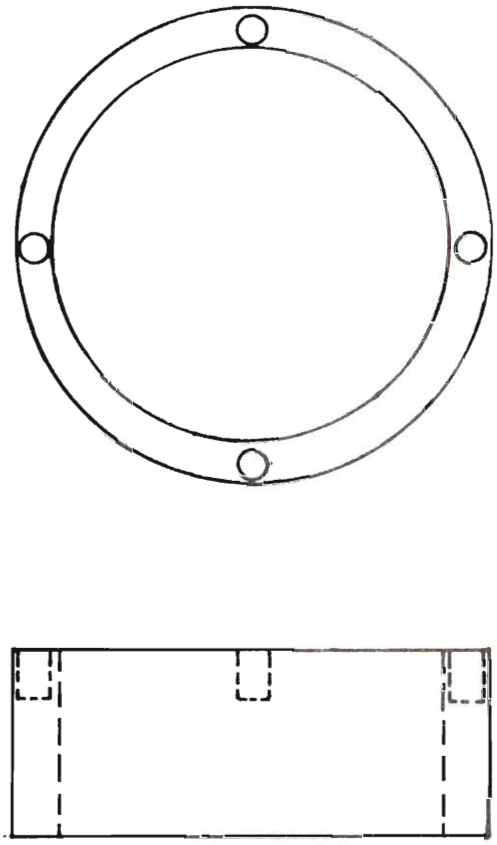


Figure 5. Die Case Used in Ram Process

cement, Ceramical. In this instance, the cement to water ratio was five to two.

Figures 6 and 7 are photographs of the master die impressions and the working die members, respectively. The master die members are not shown. These are, however, identical to the working dies except for the type of cement from which they are fabricated. All cements were obtained from the Ceramic Engineering Department.

Clay for Packing

A Kentucky ball clay ready for immediate use was supplied by Dr. Moody, of the Ceramic Engineering Department.

Model for Dies

The model piece from which the master die members were made, was fabricated by hand from a strip of polymethylmethacrylate. A photograph of this model is reproduced in Figure 8.

Hardware and Miscellaneous Items

Several small hardware items were used throughout the overall fabrication process leading to the final production of the tower packing. These were standard minor items and will be only briefly mentioned here. The register pins, steel washers, release tubing, nuts and bolts, and silicone mold release are examples of these essentials.

Equipment for Experimental Runs

General

A photograph of the column filled with the fabricated packing is reproduced in Figure 9. Figure 10 is a simple schematic diagram of the

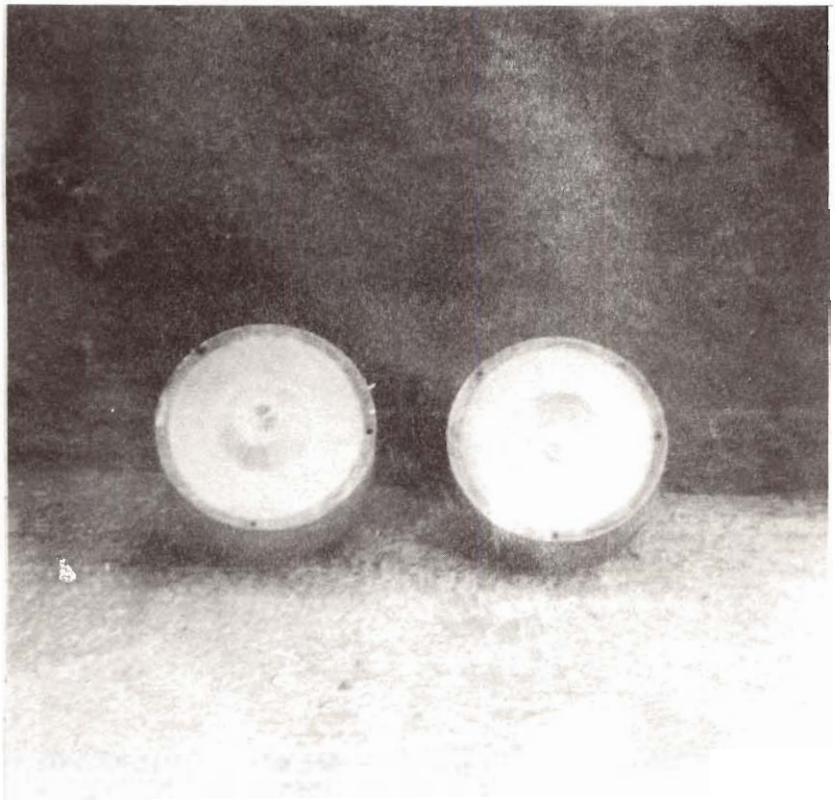


Figure 6. Master Die Impression

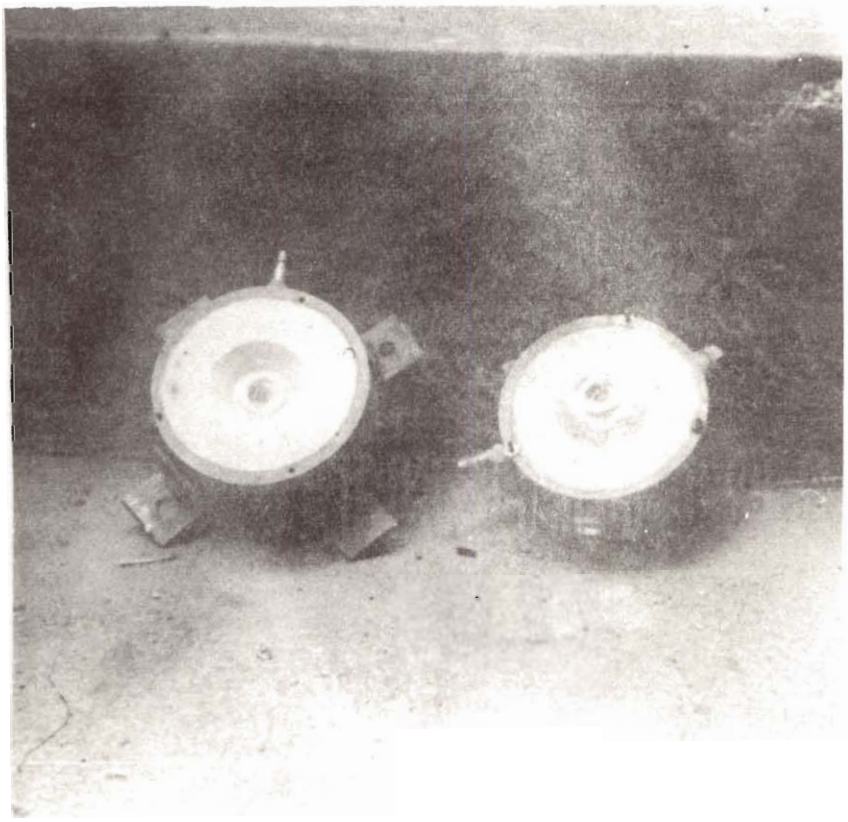


Figure 7. Working Die Members

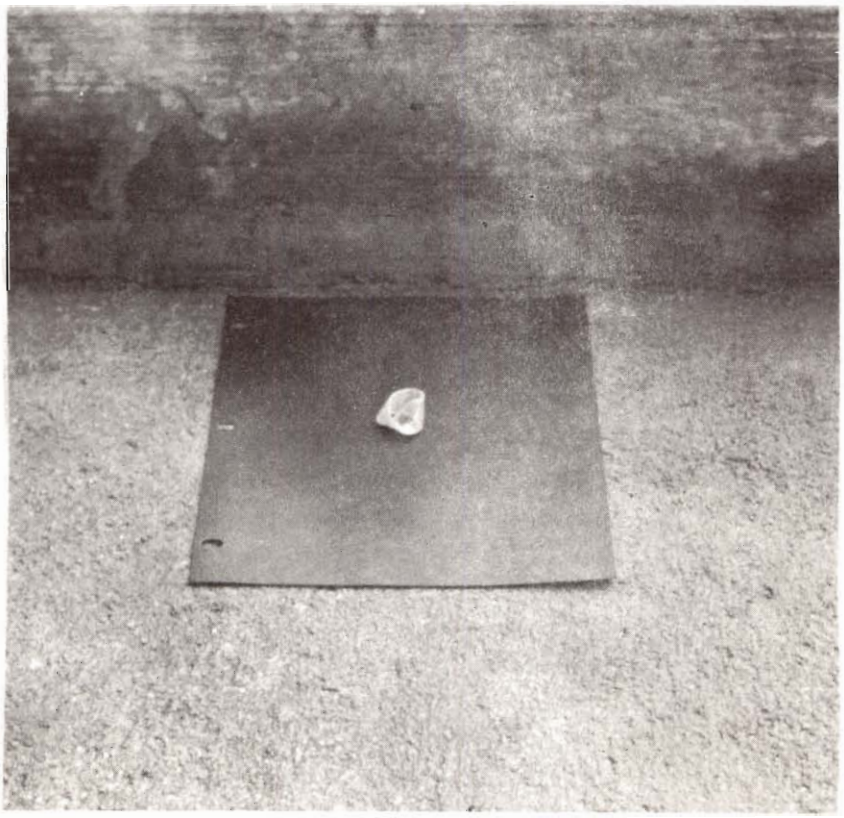


Figure 8. Model of Moebius Ring

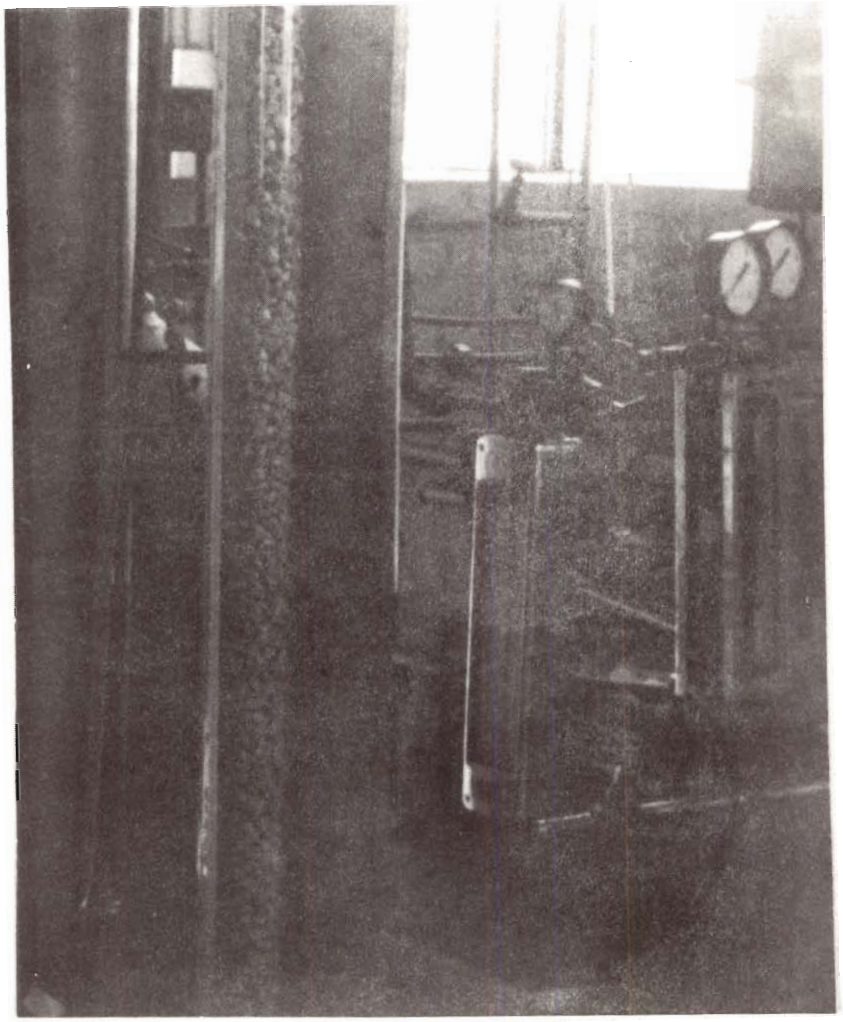


Figure 9. Column Packed with Moebius Rings

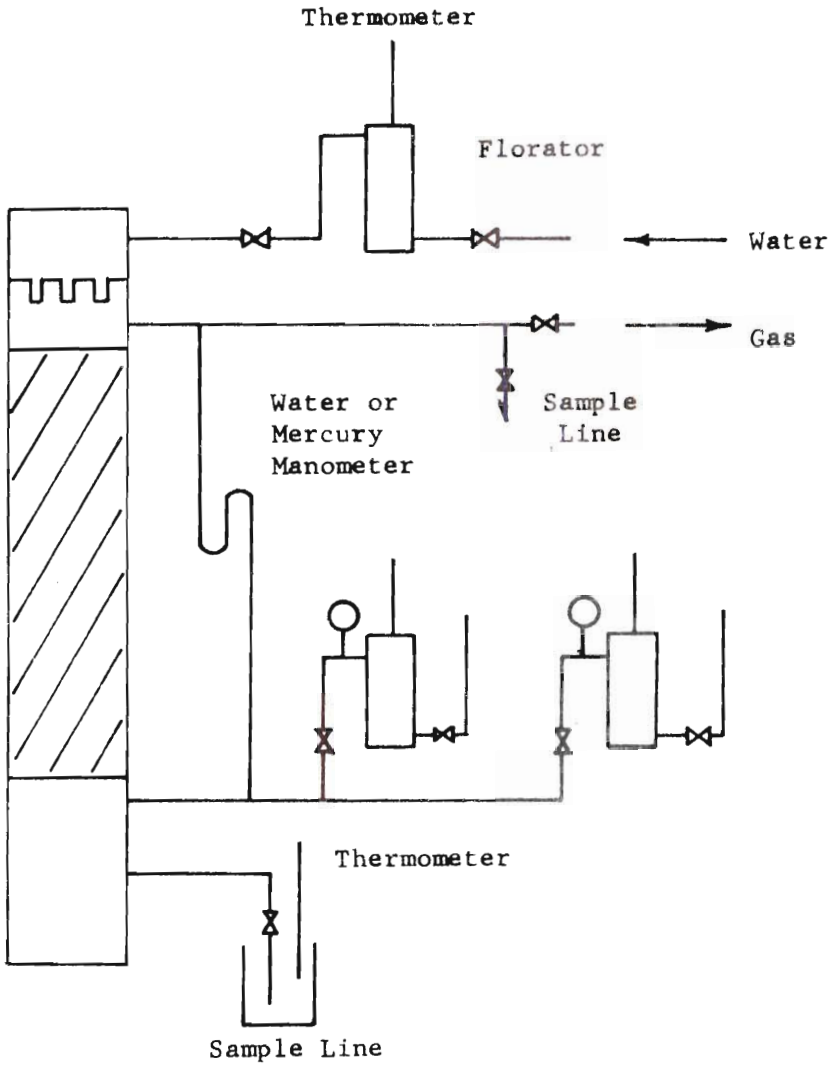


Figure 10. Schematic of Equipment

equipment setup used to measure the various characteristics of this packing.

The Column

A 3.0 inch I.D. by 5.0 feet long pyrex glass pipe was used as the basic column for measuring pressure drops. To determine the absorption coefficients, a column only 2.0 feet long was used. Each pipe was fitted with specially constructed top and bottom sections. Their purpose was to help maintain proper distribution and collection of both gas and liquid during the experimental runs.

The Top Section of the Column

The diagram in Figure 11 shows the top section of the column. For simplicity, readily available materials were used in its construction. One end of a 3/4-in. length of nominal 3-in. schedule 40 black iron pipe was centered and welded to a flat circular plate, 4.5 inches in diameter by 1/4-in. thick. To the other end of the pipe was welded a circular flat plate. The diameter of this plate was just equal to the outside diameter of the 3-in. pipe. Eight holes, each with diameter of 0.54 inch, were drilled in this fabricated piece. One hole was located in the center of the cylinder wall. The other seven holes were uniformly spaced in the smaller of the two flat plates. Into each hole was welded a 1.5 inch long piece of schedule 40 black iron pipe, nominal 1/4-in. diameter. These short pieces were so positioned that 1-1/4-in. of each protruded from each hole. Another length of 3-in. pipe was then welded to the small flat plate. This piece was 1.5-in. long. The cylinder wall was also drilled to accept a 1/4-in. piece of iron pipe. This pipe was placed 3/4-in. below the flat plate with the holes.

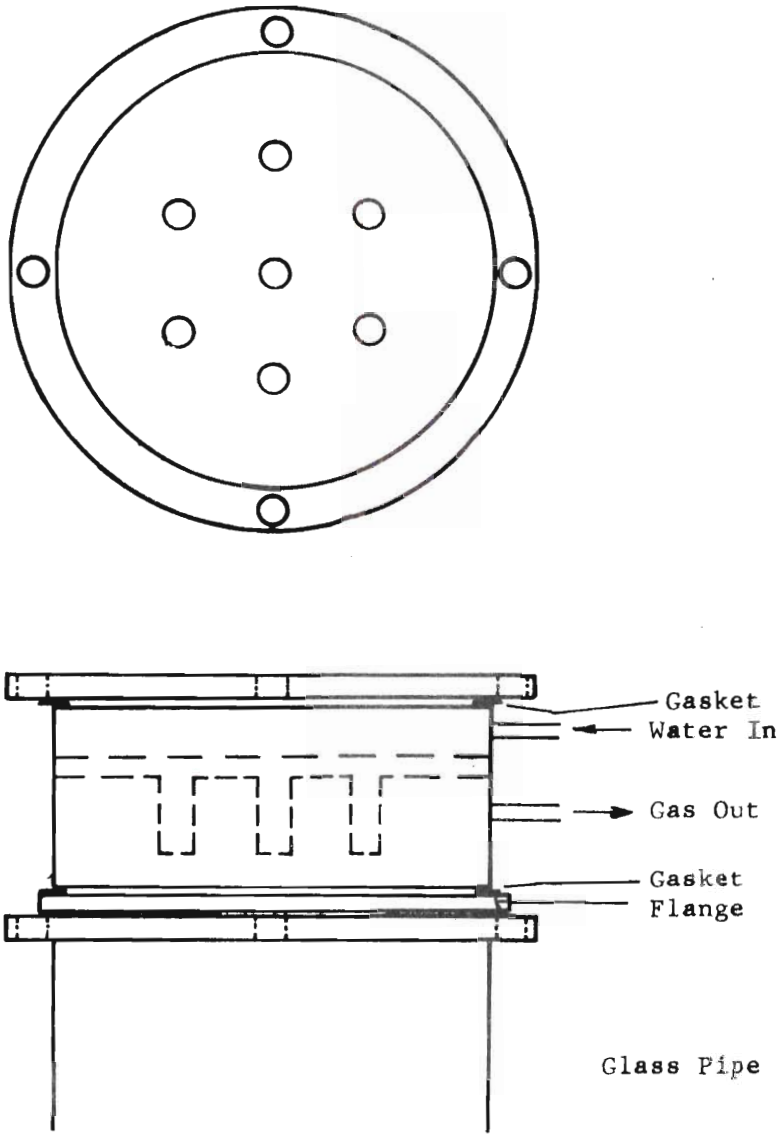


Figure 11. The Top Section of the Column

The large flat plate was drilled to match a 4.5-in. O.D. flange. This end was to be the top of the column. A flange was fitted to the glass pipe and the open end of the iron pipe was sealed to the column by means of a gasket and the two flanges. The upper 1/4-in. pipe on the cylinder wall was the intake for water, and the lower pipe was the exhaust for gases. The flat plate with the seven small pipes served as a distribution plate for water flowing down onto the packing.

The Bottom Section of the Column

A sketch of this part of the column is shown in Figure 12. To a circular flat plate, 4.5-in. in diameter and 0.25-in. thick, was welded one end of a 2.5-in. length of nominal 3-in. diameter schedule 40 black pipe. Two holes were drilled in the cylinder wall of the pipe. The diameter of each hole was 0.54-in. Their centers were located 3/4 and 1-1/2-in., respectively, from the sealed end. Into the hole close to the sealed end was welded a 1-1/2-in. long piece of 1/4-in. pipe. All but 1/4-in. of this small pipe protruded out from the cylinder wall. The other hole was fitted with a pipe so that 1-in. protruded into the cylinder and 1-1/2-in. protruded out from the cylinder. To the internal piece, a 90^{o} elbow was attached with its open end facing away from the sealed end of the cylinder. Over the open end, a small baffle was positioned to prevent water from flowing into this small pipe. To the open end of the large pipe, a circular piece of wire gauze, four mesh per inch, was attached with solder. The large flat plate was now drilled to match a 4.5-in. O.D. flange. A flange was fitted to the glass pipe and the open end of the iron pipe was sealed to the column by means of

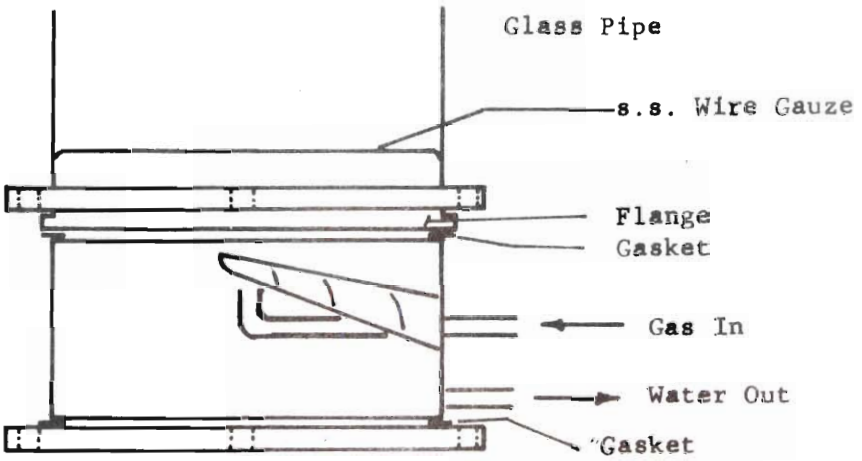


Figure 12. The Bottom Section of the Column

a gasket and the two flanges. The small pipe with the elbow was the gas intake, the other small pipe was the water drainpipe. The wire gauze was the support plate for the packing.

Manometer

A simple U-type manometer was installed across the two small pipes for gas intake and exhaust. This was done by fitting a tee-piece to both pipes. The tee thus supplied a simple tap directly in the line of gas flow into or out of the column. Two manometers were used during the experimental runs. One contained water while the other contained mercury.

Water Intake

The small water intake pipe at the top of the column was connected to a water supply line. Placed in the line for control purposes were one globe valve, a thermometer, a Fischer-Porter florater and another globe valve.

Water Drain

To the water drain pipe at the bottom of the column were connected a thermometer, a globe valve and a short piece of drain pipe leading to a small bucket fitted with an overflow pipe. The small bucket was used as a sample collector.

Gas Intake

The gas intake line was fitted with a manometer tap, and a line leading to a source of ammonia and air. Both gas lines contained a globe valve, a pressure gauge, a thermometer, a florator, and another globe valve before the tie-in to the gas supply. As seen in Figure 10, the gases could be made to flow through the column either separately or concurrently.

Gas Exhaust

The line was fitted with a manometer tap, globe valve and sample line, and a globe valve and exhaust line leading to a hood.

Valves

All the valves were of the globe type sold by Crane Company. They were made of brass, to fit 1/4-in. pipe.

Florators

The various flow measurements were carried out by using Fischer-Porter Florators. There were three of these. One each for water, air and ammonia. The calibration curves for the florators are given in Appendix 2.

Air

Compressed air was available in the laboratory. When used in the experimental runs, this air was made to flow through a sump tank, a simple water trap and a pressure regular before going to the column.

Ammonia

The ammonia source was from a standard tank of commercially available dry ammonia.

Laboratory Supplies

Analytical chemical reagents, pipettes, burettes, thermometers, glassware, and other standard laboratory supplies need no further description.

CHAPTER III

PROCEDURE

Fabrication of Packing

The Ram Process

The Ram Process is the mechanical hydraulic plastic pressing of ceramic shapes with gypsum cement dies. Instant release of the pressed shape may be obtained by means of fluid pressure forced through the permeable die. Any shape that can be made in a two-piece mold can be adapted to the Ram Process. Each Ram die consists of two members; usually a male and female member. These dies are encased in metal die casings and are provided with registration pins for proper alignment of the members. The gypsum cement body is internally reinforced to provide for the pressure requirements. The body may range from 100 per cent clay to 100 per cent non-plastic. Generally, the clay charge should be of a "stiff mud" consistency.

Preparation of Model for Die Fabrication

It was decided that the packing ring should have essentially the same surface area as a Raschig ring of similar dimensions. Thus, a standard 1/2-in. stoneware Raschig ring has the dimensions 1/2-in. O.D. x 1/2-in. H. x 3/32-in. wall thickness. It may be fabricated by rolling a rectangular strip of plexiglas, 1/2-in. wide, 1.57-in. long and 3/32-in. thick, into a cylinder and sealing the butt ends. A 1/2-in. moebius ring could be formed by using an identical rectangular strip. Before sealing

the butt ends, however, a single continuous twist must be incorporated into the cylinder. This was the method that was used to prepare the model for the Ram dies. It was essential, however, to consider the shrinkage and expansion inherent to the cements and clay to be used in the various steps leading to the production of the packing ring. Through trial and error, it was found that the model should have the dimensions of a 3/4-in. Raschig ring if a 1/2-in. moebius ring was desired. That is, the rectangular strip would be, 3/4-in. wide, 2.34-in. long and 1/8-in. thick.

This rectangular strip was cut from a sheet of 1/8-in. thick Plexiglas. To make the strip flexible, it was placed in an oven of 350°F. After several minutes, the strip was removed from the oven, immediately twisted once, turned to butt the ends, and cooled in that position. Ethylene dichloride solvent was used to seal together the butted ends. The resultant ring was rather lopsided. To correct this, it was returned to the oven for several minutes. Because of its so-called memory property, the Plexiglas had a tendency to return to its original shape of a flat strip. The seal, however, prevented this. Consequently, a plastic ring was obtained that was not lopsided and whose shape could be simply and identically reproduced. Figure 13 shows several plastic rings in various stages of forming before the final Plexiglas model is attained.

Preparation of Plaster for Master Die

A standard mix of pottery plaster was used for the Master Die. Five pounds of No. 1 plaster were gently sprinkled into 3-1/2 pounds of distilled water at 81°F. During the sprinkling, the mixture was very gently stirred by hand. Extreme care was exercised to minimize the

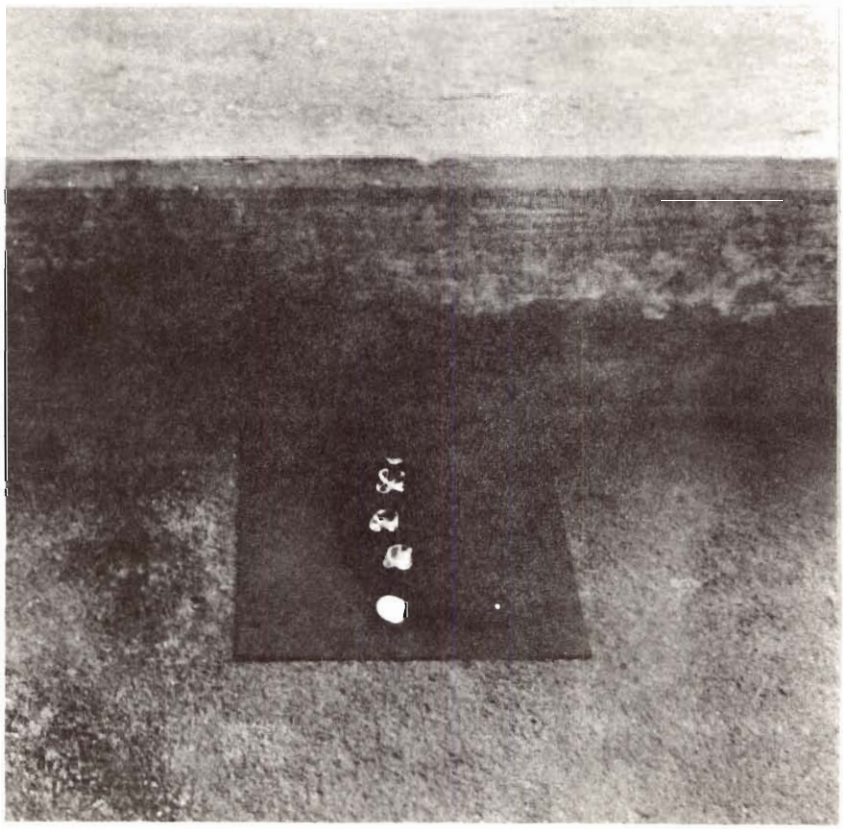


Figure 13. Formation of Plastic Moebius Ring

entrainment of air into the mixture. The stirring was continued for about 20 minutes. At the end of that time, the mixture began to thicken. The mixture was now constantly checked by hand for consistency. When it reached the consistency of a heavy cream, it was ready for immediate pouring. After pouring, the plaster set very quickly and could be reasonably handled within 15 minutes without cracking or crumbling.

Preparation of Cement for Master Die Impressions

It was necessary to prepare Master Die Impressions from the Master Die members. A hard gypsum cement was used for this purpose. Specifically, the B-11 Hydrocal was mixed with water in the ratio of six pounds of Hydrocal to three pounds of water for each die. The procedures for mixing, stirring, and determination of consistency were identical to those given above for the preparation of the No. 1 plaster mix.

Preparation of Cement for Working Die Members

The working die members were prepared from the Master Die impressions. Here, too, a hard gypsum cement was used. Since the working die members must be made permeable to air, Ceramical cement was used. A ratio of 7.5 to 1 of Ceramical to distilled water was used. The cement and water were mixed mechanically with a high-speed propellor-type mixer. Care was taken to prevent the introduction of air into the mixture. The mixing was continued for 22 minutes at which time further mixing was continued by hand. When the mixture had a creamy texture, it was ready for immediate pouring.

Preparation of Master Die Member

The model of the piece was prepared as described above. Although it should preferably be of plaster, Plexiglas offered the advantage of

ease of fabrication. Tedious whittling and measuring were eliminated. Further, the final shape would be dictated only by the dimensions of the flat strip of plastic. The preparation of the Master Die members proceeded as follows:

(a) The surface of the plastic model was thoroughly soaped with a solution of sodium stearate. As the water evaporated, a thin film of soap formed on the plastic. This film imparted mold release to the plastic so that it could be easily parted from plaster poured against it.

(b) The model was centered in the die casing with the parting line level and at the level desired in the die ring.

(c) The model was blocked in place with putty. Plastic clay, or modeling clay may be also used for blocking. Figure 14 shows a simple shaped model in the blocked position.

(d) The surface of the blocking material was smoothed and shaped to the desired contour.

(e) The putty and model were soaped and resoaped.

(f) A second die casing was placed in position by registering with pins in the registration holes. It was made certain that the metal rings were in intimate contact. This second die was now filled with No. 1 pottery plaster. In pouring the plaster, caution was taken to prevent air being trapped on the surface of the model or blocking material. Figure 15 shows the position of the dies for this first pour.

(g) The plaster was allowed to set and the die rings were separated.

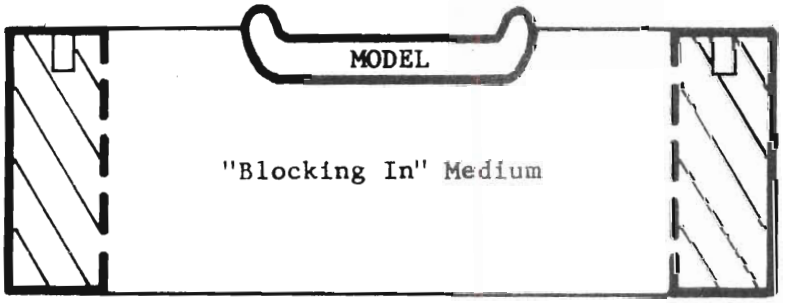


Figure 14. Setup for Master Die

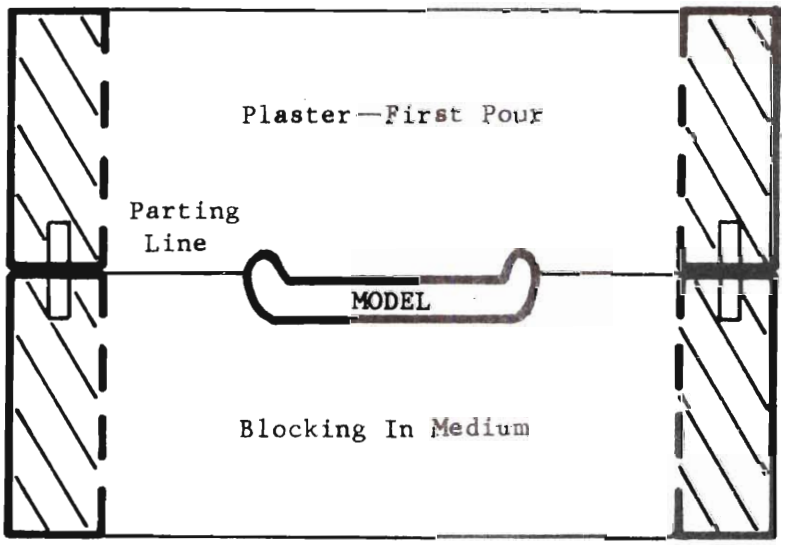


Figure 15. Die Positions for First Pour

(h) The blocking material was cleaned from the surface of the plaster. The contour desired in the plaster was obtained by dressing and smoothing the surface. The model and die were tested for tightness of fit. A slightly loose fit was desired.

(i) The model and plaster area were well soaped. The model was placed into position in the die and the combination was resoaped.

(j) The first die ring was cleaned, placed back in position and registered as before. In registering the rings, spacer washers were used at the registration pins between the two rings to separate the two die casings about 1/8-in. The adjustable space was provided between the casings so that the Working Die Members could be brought closer together during the working life of the die. This is necessary to counteract a growth in the seam or fin that would occur due to die wear at the cut-off point. The spacer washers were precision machined items to ensure that they were of identical thicknesses. See Figure 16 for second pour position.

(k) The die ring was filled with the No. 1 plaster mix. In pouring the mix, care was exercised to prevent entrapment of air on the surface of the model or plaster area.

(l) When the plaster was set, the die rings were separated and the model was removed.

(m) The surface of each die was dressed, gutter areas were carved, and the dies were smoothed and finished where necessary. Figures 17 and 18 show the carving of the gutters and the completed Master Die Members, respectively.

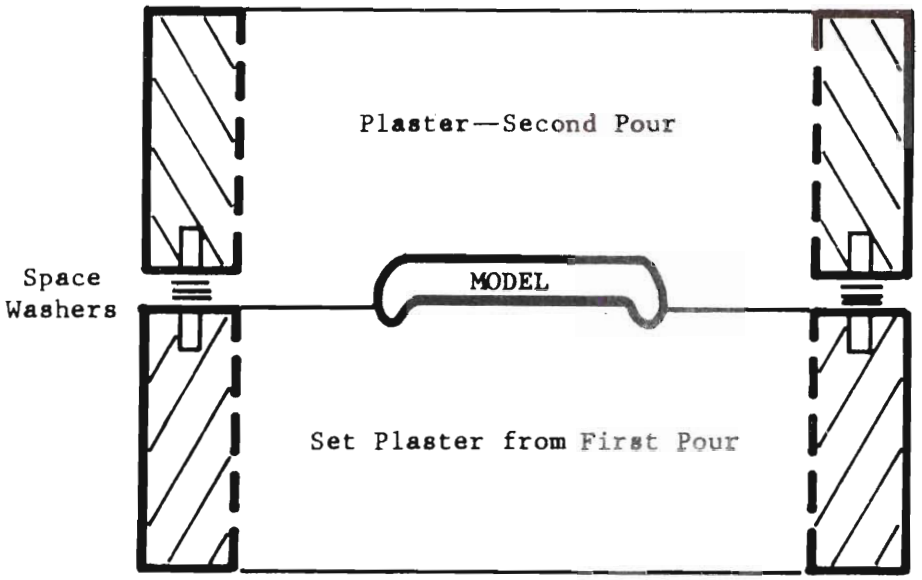


Figure 16. Die Position for Making Second Pour for Master Die

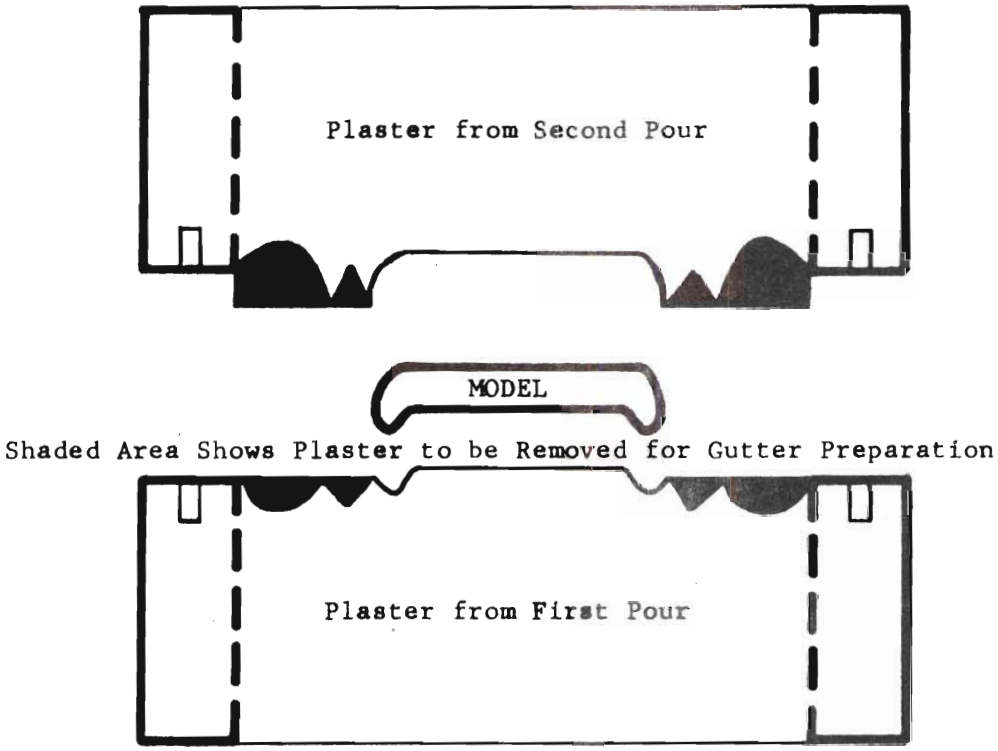


Figure 17. Cutting of Gutters in Master Die

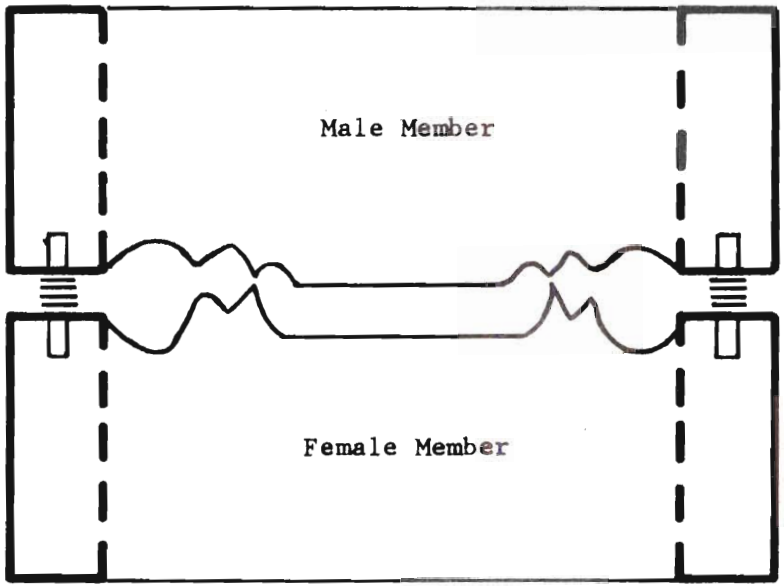


Figure 18. Completed Master Die

(n) Due to expansion of the plaster, if placed together, the two dies must be separated by double the separation provided during pouring.

Preparation of Master Die Impressions

The Master Die impressions are the reverse of the Master Die Members and the Working Die Members were made from them. These impressions were made out of the B-11 Hydrocal cement prepared as described below. The preparation of the dies proceeded as follows:

(a) Both members of the Master Die were thoroughly soaped.

(b) Clean die rings were placed in intimate contact with and in position on both the Master Die Members. The rings were correctly registered to enable the impressions to fit together properly.

(c) The Hydrocal mixture was poured carefully to prevent air entrainment.

(d) When the mixture was set, the rings were parted.

(e) Where required, the face of each Die Impression was smoothed and touched up.

(f) The face of each Die Impression was coated with a thin solution of shellac and alcohol (1:10). The coating was applied until a luster appeared on the surface to indicate no further penetration of shellac into the cement.

(g) Each Impression was thoroughly soaped and placed on its side to dry so that the drying took place from the back.

Preparation of Working Die Member

The Working dies are an integral part of the Ram Pressing Operation. Their quality, therefore, plays a major part in governing the efficiency of

the pressing process and fabrication of the final product. The stepwise procedure that was followed in preparing the Working Die Members is listed here:

(a) The Master Die Impressions were thoroughly soaped.

(b) The casings equipped with the coupling for an air hose were used for the Working Die Members.

(c) The release coil mechanism was placed in each die ring. This mechanism was made from Fiberglas tubing. It is permeable to air, flexible, but resistant to collapse. A more detailed description of the release unit design and placement is given elsewhere in this chapter.

(d) Each die ring was placed in position on the Impression Members. The aligning pins were used to register the dies; the air hose adapter fittings were aligned one above the other; and, the metal rings were in intimate contact.

(e) The Ceramical cement was mixed, poured into the die, and allowed to set.

(f) The air hose was hooked up. As soon as the initial set had taken effect, the air purge schedule was started. The purge was necessary to induce permeability. It was accomplished by applying air pressure through the release coil mechanism to blow or drive out the excess water used in the cement mixture. The purging schedule was quite simple. It was started five minutes after initial set with air pressure controlled at ten pounds per square inch. After 30 seconds, the air pressure was increased to 20 p.s.i. Thereafter, every 30 seconds, the air pressure was increased by 10 p.s.i., until a pressure of 100 p.s.i. was attained.

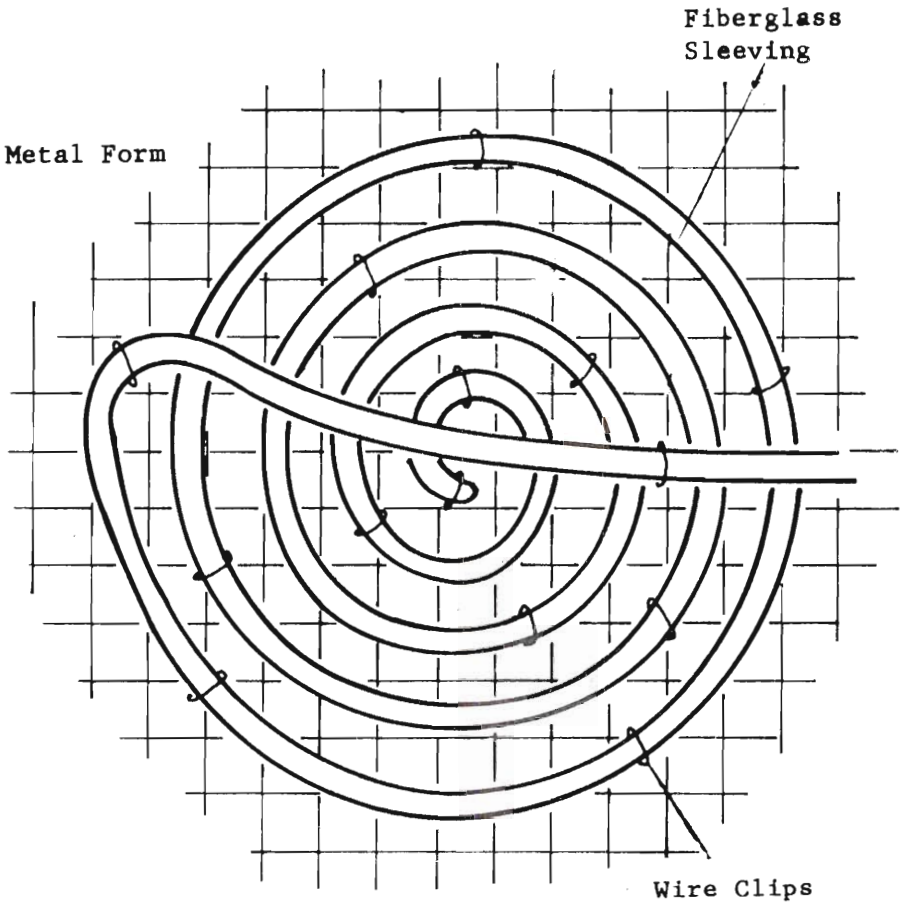
(g) The Working Die separated easily from the Die Impression immediately after the initial purge with air was completed.

(h) During the purge period, the Working Die was placed on its side. The face of the die was sponged frequently.

(i) When completely purged, the Working Dies were mounted into position on the Ram press. They were now ready for the pressing of the packing rings.

Release Unit Mechanism

The release unit was encased within the Working die to allow for the introduction of compressed air. The air must be properly distributed to release the formed ware from the die. An equally important function was for introducing the compressed air into selected portions of the Working die for purging during the die making procedure. Various materials could have been used for this purpose. The choice in this case was a permeable fiber glass sleeving which had been annealed to induce a degree of rigidity. The fiberglas sleeving did not retain a formed shape. Consequently, to serve as the release unit, it had to be formed on a retaining member. Two steps were necessary to attain the proper form. First, an annealed iron wire was inserted in the sleeving and bent to the desired shape. Next, the formed sleeving was fastened to a 1/2-in. mesh metal cloth. The general shape imparted to the sleeving was that of a helical coil. The sleeving was spaced not farther apart than the distance from the sleeving to the face of the die. Nor were the coils of the sleeving wound closer together than the diameter of the sleeving. Figure 19 shows the general positioning of the release unit in the male Working Die Member.



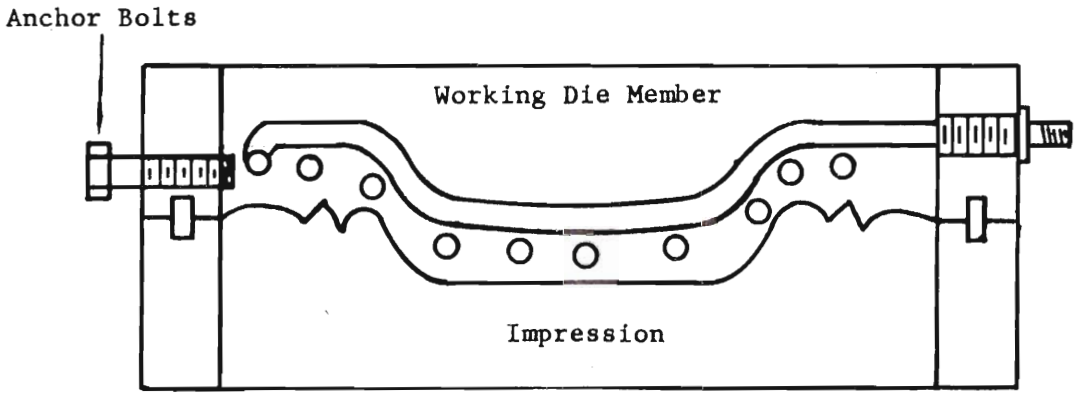


Figure 19. Ware Release Unit

Operation of Ram Process

The novel feature of the Ram Process is that of the release of the formed ware from a permeable cement die. This is accomplished by blowing air through the die to affect the release. The pressed ware adheres rigidly to the die until released by the air. The stepwise procedure for pressing the ware and for releasing it from the die member is as follows:

(1) The male and female dies were mounted into position on the Ram press. The registering pins were used to align the dies. The press was adjusted so that the male member could not descend too far onto the female member to cause cracking of a die.

(2) The clay charge was extruded to give a long solid rod of about 3/4-in. diameter. This was cut into small disks of 3/4-in. diameter and 1/4-in. height.

(3) The clay dish was placed on the lower die member.

(4) The press was activated; the dies were brought into registration, thus spreading the clay charge and forming the ware in the cavity of the die.

(5) Air was applied to the lower die member to release the formed ware from it. When the press ram was allowed to return to the open position, the formed ware adhered to the upper Working Die Member.

(6) Air was now applied to the upper die member. This allowed the adhered formed ware to drop off.

(7) The formed ware was placed on a table top and allowed to air-dry overnight. After air-drying, it was further dried and processed by

firing in an oven. The firing was accomplished after the ware had been exposed to a temperature of about 2000°F. for approximately four hours.

(8) The flash from the ware was removed after the firing was completed.

(9) The air applied for release of the formed piece from the upper die and was left on very briefly. During this time, the water picked up by the die members in the pressing operation was forced to the surface of the die. Before recharging the die with clay, the air was shut off and the water was sponged from the die surface. The sponging operation was only sufficiently adequate to approximately remove the water which was picked up during the pressing; the original water in the die must remain in the die members.

Preparation of Clay

The clay was prepared by students of the Ceramic Engineering Department according to the standard techniques of mixing and deaeration.

Evaluation of Packing

General

The calibration of florators, standardization and titration of solutions are generally well-known procedures. Pertinent data are, therefore, presented in Appendices 2 and 5.

Packing of the Column

It was desirable to have a random arrangement of the packing in the column. To obtain this the column was prepared as follows: The bottom section was attached to the glass pipe. The column was then partially filled with water. Pieces of the fabricated packing were

individually dumped into the water and allowed to settle naturally. This procedure was continued until a packed height of four feet six inches was attained in the column. The top section was fitted to the column, thus, making the column ready for the experimental runs.

Pressure Drop

With the column operating at various gas and water flow rates, the pressure drops were measured by means of a manometer. For low pressure drops, a water manometer was used. When the water manometer became impractical because of higher pressure drops, a mercury manometer was substituted. For each particular air and water flow combination, the column was allowed to operate for at least 15 minutes before a pressure drop reading was recorded. Preliminary experiments showed that this time was sufficient for equilibrium to be established. Each run was repeated four times to obtain average values.

The runs for pressure drop determinations followed a definite sequence. The air and water valves were turned on. The air flow was adjusted to that desired by means of the valves and the calibrated florator. The water flow was now shut off and the column was allowed to drain. When completely drained of water, the column was allowed to equilibrate at the pre-set air flow. After equilibrium was established, the pressure drop was recorded. The water was again turned on and set for a desired flow rate. The air flow rate was left unchanged. After equilibrium was again established in the column, the pressure drop was recorded. This procedure was repeated until the pressure drops were recorded for seven water flow rates for each of ten air flow rates. Also recorded were the data for the dry packing and wet and drained packing

for each air flow rate. This whole procedure was completely repeated four times in the same prescribed sequence. To correct for the apparent high pressure drops due to the support and distribution plates, the air flow experiments were repeated with the unpacked column. Since the absence of packing eliminated liquid holdup, the water rate was zero for these runs. The pressure drop across the dry packing for different air flows was also recorded. To be consistent with the data reported in the literature, effects such as wall friction were neglected.

Void Volume

A bulk volume of one cubic foot of the packing was poured into a container filled with one cubic foot of water. The container had a diameter of one foot and was two feet high. By simply measuring the amount of water displaced, it was possible to determine the void volume of the packing.

Specific Surface

The total surface area per cubic foot of packing was calculated from the dimensions of the fabricated piece and the number of pieces in a packed volume of one cubic foot.

Absorption of Ammonia

Water, air, and ammonia were allowed to flow through the column. The air and ammonia flow rates were adjusted to specific quantities. While maintaining these flows, the water rate was set. The column was run at these set flows for one-half hour after a constant temperature established equilibrium. Then, four 50.0 ml. samples of water effluent were collected ten minutes apart and pipetted into 100.00 ml. of hydrochloric acid solution. The resulting solution was backtitrated with a

standard sodium hydroxide solution to a phenophthalein end point. The water flow rate was adjusted to a new value and the experiment repeated. In all, four water rates were used for this combination of air and ammonia flows. This complete procedure was then repeated for each of eight additional combinations of air and ammonia flows. For each case, the molar ratio of ammonia flow to air flow was maintained constant when the gas flows were re-set. For each run, the temperatures of the inlet water, the effluent water, the ammonia inlet flow and the air inlet flow, were recorded. The atmospheric pressure and temperature were also recorded.

Holdup

The water flow through the column was adjusted as desired. After equilibrium was established the water to the tower was shut off. The quantity of water that drained from the column during a period of five minutes after the feed had been shut off was collected and measured. This was the operating holdup for that particular water flow.

CHAPTER IV

RESULTS AND DISCUSSION

New Packing

The Ram Process for fabricating the new packing was found to be convenient and simple. The packing pieces were made without any particular difficulty, once the variables of production became known. The use of dies capable of pressing only one ware at a time, however, proved to be tedious work. Dies that could press a dozen or more pieces at a time would eliminate the slow rate of production. Observations of the fabricating procedure indicated that the packing could be readily formed by methods applied to the fabrication of Berl and Intalox saddles. For this reason, it is believed that the commercial production of the new packing could be economically competitive. A rigorous economic evaluation study would require knowledge of such factors as the maximum possible rate of production, the efficiency of the packing in absorption, the resistance offered to the flow of fluids through the packing, the strength of the packing, and the materials of construction. The evaluation of some of these items is beyond the scope of this thesis.

A measure of some of the physical characteristics of the packing showed that there were approximately 9000 rings per cubic foot of packing. The surface area was approximately 104 square feet per cubic foot and the void space was found to be 63 per cent. Since this packing is a nominal size of 1/2-in., it can readily be compared with 1/2-in.

Raschig rings, Berl saddles, and Intalox saddles. This can best be done by tabulation as in Table 4.

Table 4. Comparison of 1/2-In. Packing

Packing	Approximate Number per Cubic Foot	Approximate Surface Area Square Foot/ Cubic Foot	Per Cent Free Space
Raschig Ring	10,700	114	53
Berl Saddle	16,200	142	63
Intalox Saddle	20,700	190	78
New Packing	9,000	104	63

The new packing apparently takes up 16 per cent more space than the equivalent Raschig ring and, therefore, offers less total surface area for mass transfer.

Pressure Drop

The pressure drop across the packing was measured at water flows of zero, wet and drained, 1225, 3675, 4900, 6125, 7810, 9371, and 10945 lbs./hr./sq. ft. for air flows of 63, 127, 190, 253, 317, 380, 443, 537, 570, and 633 lbs./hr./sq. ft. The results are tabulated in Table 5 and plotted in Figure 20 to show the relationship between pressure drop per foot of packing and gas flow for various constant water flows. Below the flooding region, the pressure drop varied as expected according to the theory of White (16). The pressure drop per foot of packing was found to be very nearly proportional to the 1.8 power of the gas flow.

Table 5. $\triangle P$, G, and L for Moebius Rings

G	PRESSURE DROP IN INCHES WATER PER FOOT AT VARIOUS L								
	Dry	W&D	1225	3675	4900	6125	7810	9371	10,945
63			0.013	0.018	0.022	0.024	0.047	0.064	0.080
127	0.018	0.024	0.047	0.058	0.078	0.091	0.014	0.19	0.24
190	0.033	0.051	0.10	0.12	0.16	0.19	0.26	0.35	0.44
253	0.056	0.084	0.19	0.21	0.29	0.35	0.44	0.60	0.68
317	0.082	0.12	0.29	0.35	0.45	0.55	0.65	0.87	1.36
380	0.12	0.18	0.38	0.50	0.60	0.80	1.05	1.41	3.41
443	0.15	0.23	0.61	0.80	0.87	1.08	1.50	2.71	
507	0.19	0.30	0.86	1.10	1.30	4.70			
570	0.24	0.37	1.20	1.70	4.70				
633	0.30	0.45	1.60	3.10					

G = Lb. moles air/hr./sq.ft.

L = Lb. moles water/hr./sq.ft.

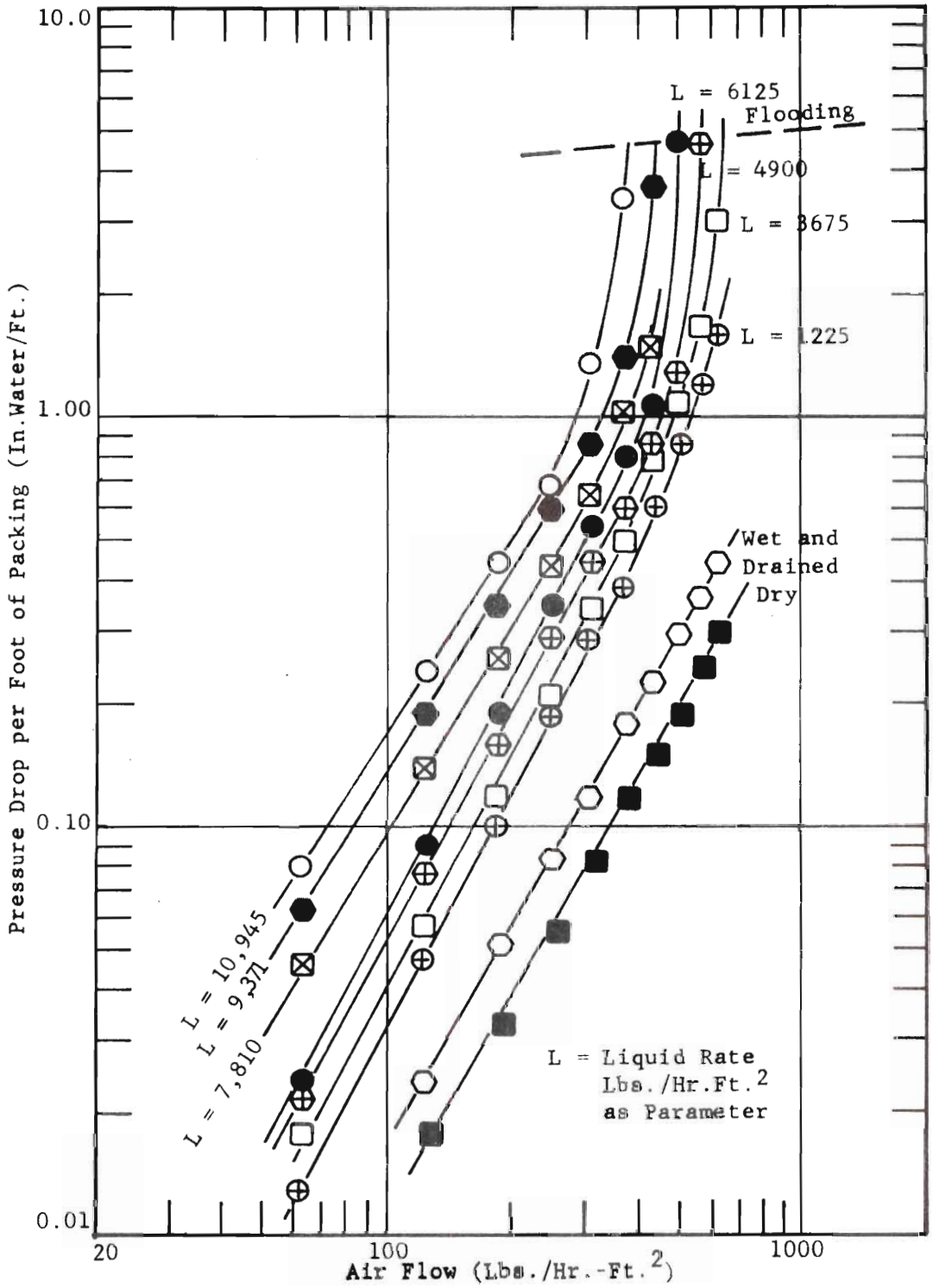


Figure 20. Pressure Drop vs. Air Flow

The actual exponents of the gas flows for various constant water flows are presented in Table 6. It is seen that the exponent decreases from 1.90 to 1.56 when the water rate increases from 1225 to 10945. As the flooding region is approached, the pressure drop increases very rapidly with increasing air flows until the tower becomes inoperable. Flooding occurred when the pressure drop was 4.6 inches of water per foot of packing at a water flow of 10,945 lbs./hr./sq.ft. and an air flow of 390 lbs./hr./sq. ft. For water and air flows of 4900 and 640 lbs./hr./sq. ft., respectively, the pressure drop was 4.8 inches of water per foot of packing. Figure 21 shows air and water flows at the flooding region. Several corresponding pressure drops are inserted at appropriate points on the curve. Figure 22 shows the relationship of gas flow to water flow at constant pressure drops below the flooding region. It is really another method of presenting the data of Figure 20; however, it has been included here for the reader's convenience.

Although the pressure drops through various packing have been studied by many researchers, there are little data in the literature on studies carried out in three-inch diameter columns. Since the size of the tower affects the pressure drop, data for 1/2-in. Raschig rings will be different in a six-inch column than in a three-inch column. Therefore, there would be little value in comparing the pressure drops across the new packing in a three-inch diameter column with pressure drops for other packing in columns of different diameters. Nevertheless, it might be reasonable to assume that the relative pressure drops of specific packings are the same in any given column. If so, the pressure drops across many packings may be indirectly compared to the pressure drops

Table 6. Exponents for the Relationship of Pressure Drop vs. (Gas Flow)[a] for the New Packing at Constant Liquid Rate Below Flooding

L (Lbs./Hr./Sq.Ft.)	a
1225	1.90
3675	1.88
4900	1.86
6125	1.90
7810	1.66
9371	1.62
10,945	1.56

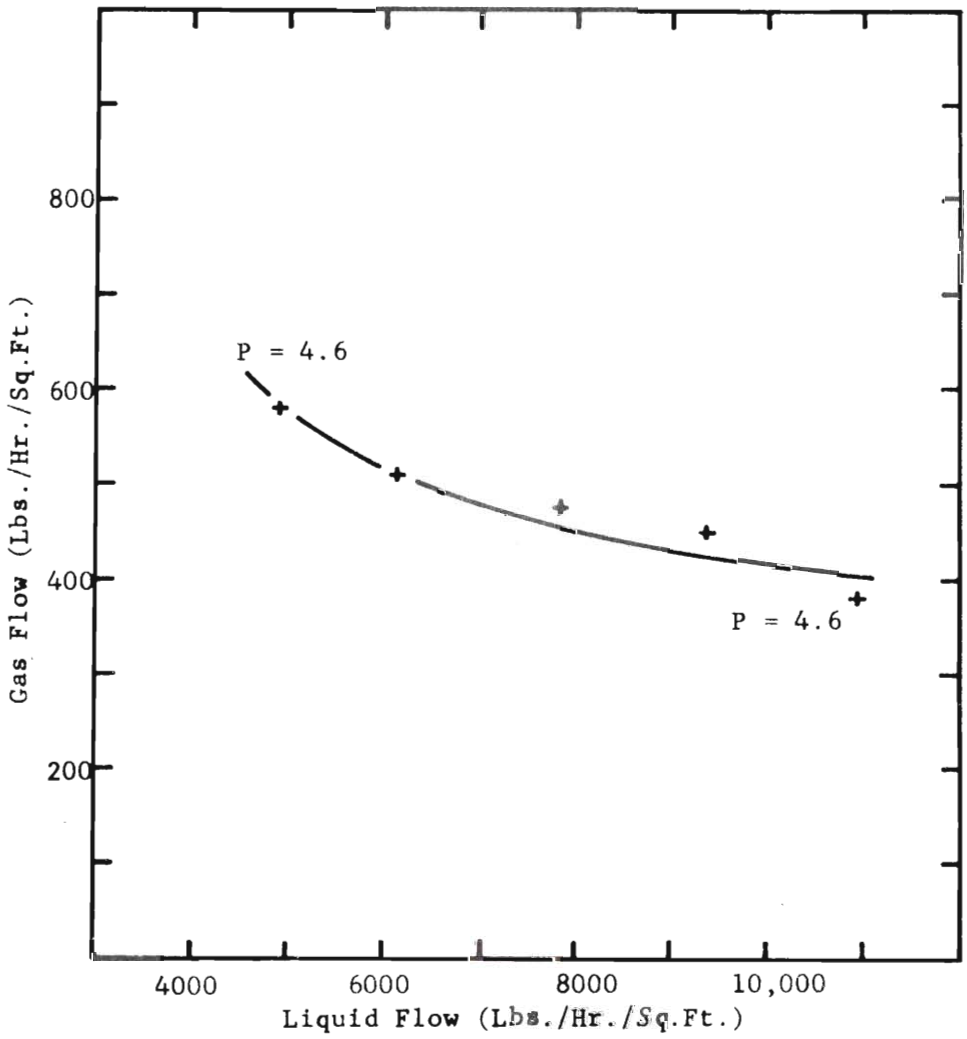


Figure 21. Gas Flow vs. Liquid Flow at Flooding

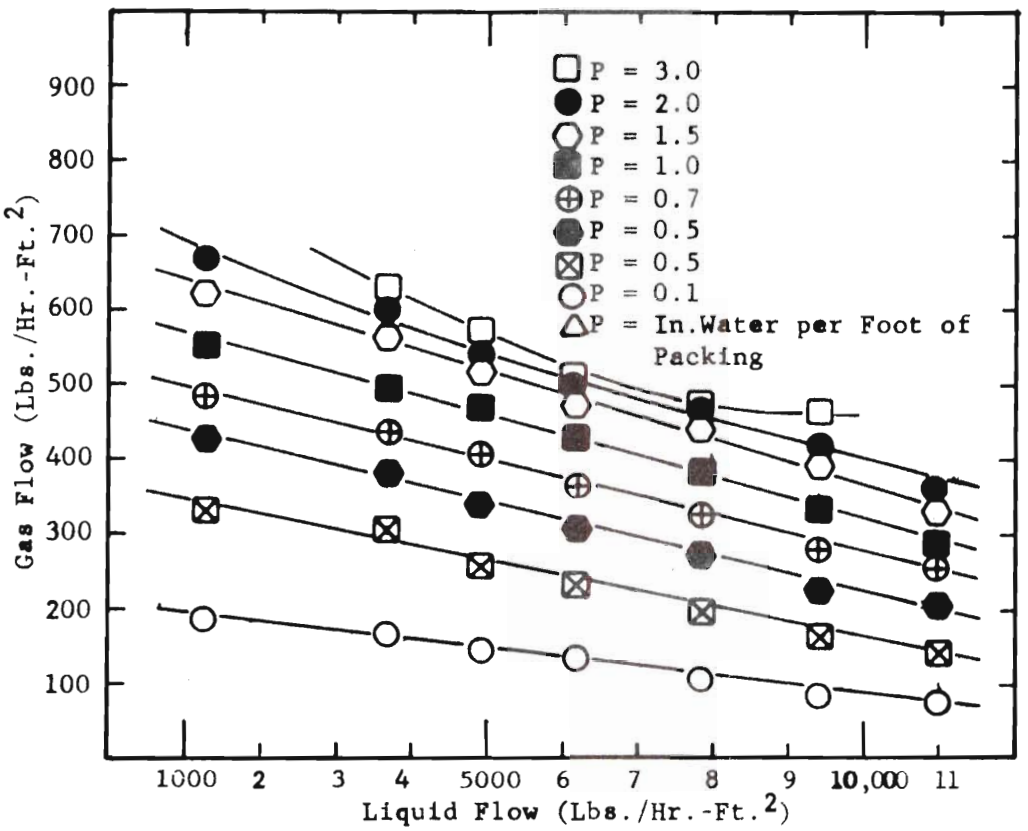


Figure 22. G vs. L at Constant ΔP for New Packing

across the new packing. For example, pressure drop data are available for ceramic 1/2-in., 3/4-in., and 1-in. Raschig rings, Berl saddles, and Intalox saddles all measured at the same conditions in a 30-in. diameter column. This data is found in the U. S. Stoneware Publication, Tower Packing (19). From this data, it is possible to calculate the ratios of the pressure drops across any of the packings to the pressure drop across the 1/2-in. Raschig rings in the same column. The results obtained by White (16) for a 3-in. diameter column allow the calculation of the ratios for pressure drops across the new packing to the pressure drops for 1/2-in. Raschig rings in a 3-in. column. By directly comparing the proper ratios from the 30-in. column with those from the 3-in. column, one may obtain the relative pressure drop across any standard packing to the pressure drop across the new packing for the same basis of measurement. The results of such calculations for Raschig rings, Berl saddles, and Intalox saddles are shown in Figures 23, 24, and 25, where the ratios of the pressure drops of 1/2-in., 3/4-in., and 1-in. packings, respectively, to the pressure drops of the new packing are plotted against the gas flows at several constant water flows. For dry packing, 1/2-in. Raschig rings show 62 per cent higher pressure drops, 1/2-in. Berl saddles 32 per cent pressure drops, and Intalox saddles 57 per cent lower pressure drops, than the new packing for gas flows between 200 to 600 lbs./hr./sq. ft. For the same gas flows but at the constant water flows of 3600 lbs./hr.-sq.ft., the relative pressure drop of 1/2-in. Raschig rings to new packing decreases from 1.0 to 0.7. Similarly for 1/2-in. Berl saddles it decreases from 0.35 to 0.18 and for 1/2-in. Intalox saddles from 0.16 to 0.12. At constant water flows of 5350, the

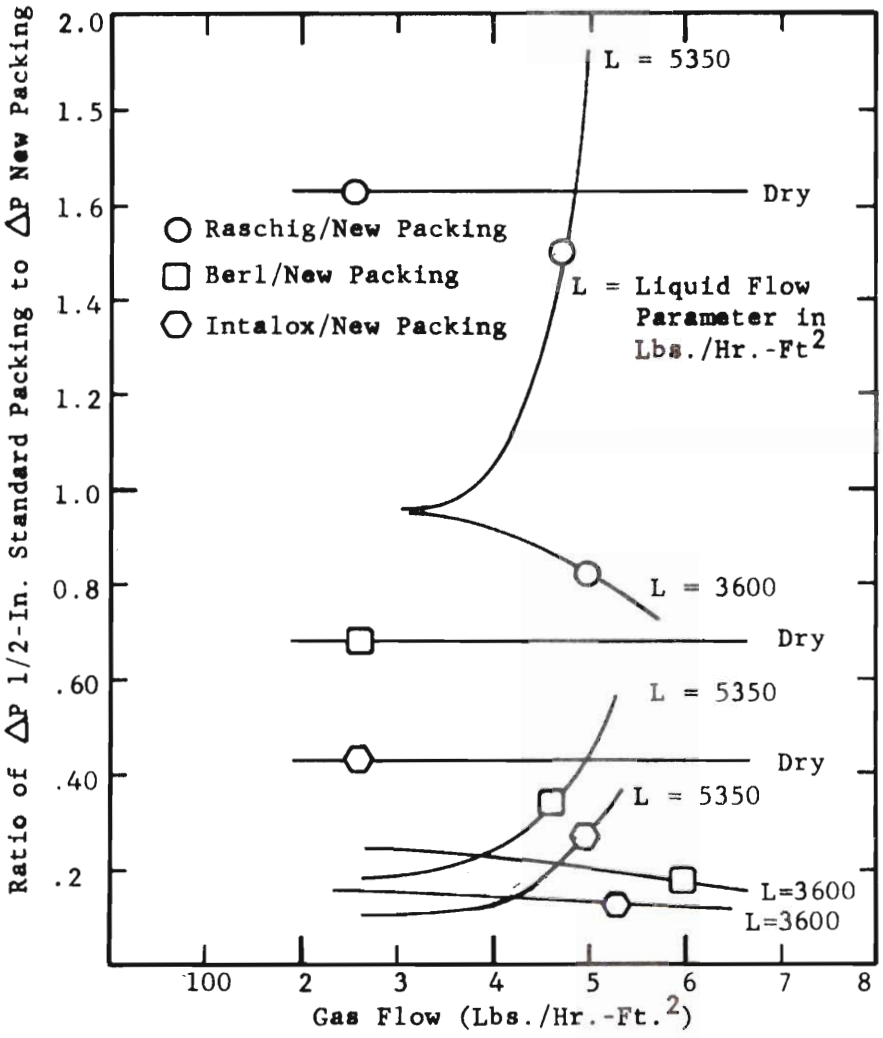


Figure 23. Ratio of Pressure Drop of 1/2-In. Standard Packing to New Packing vs. Gas Flow

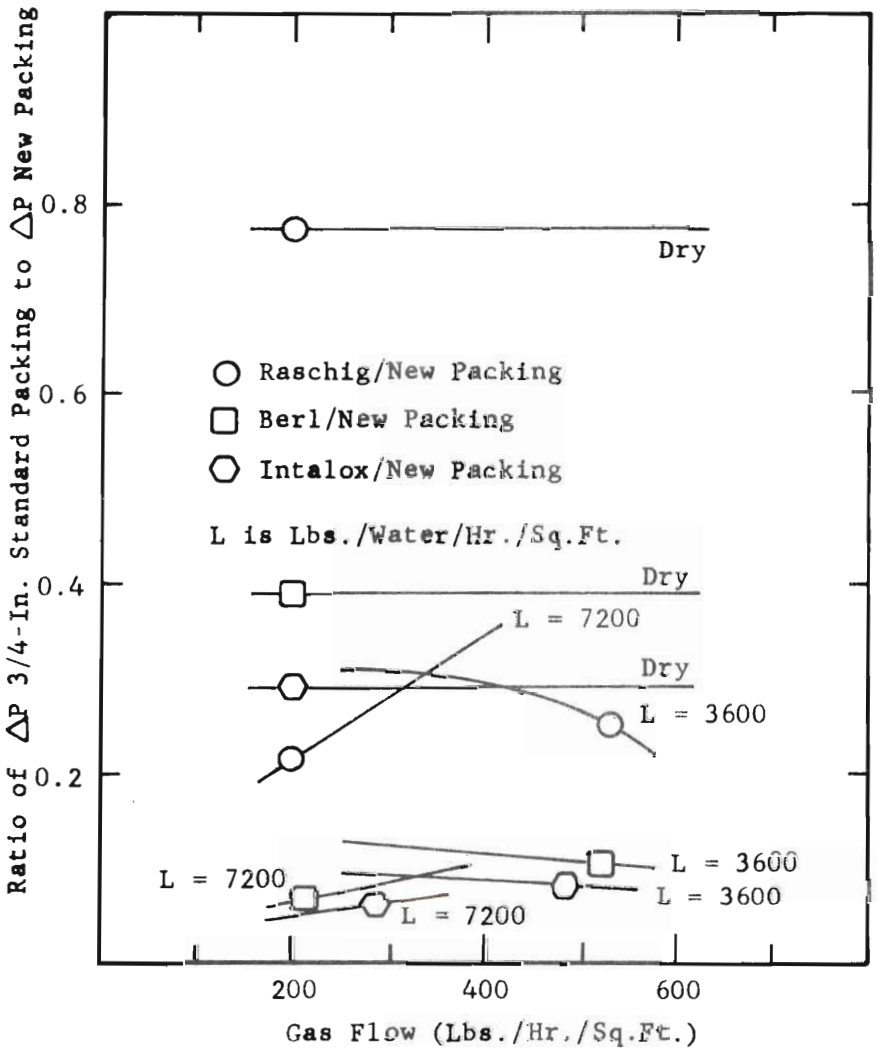


Figure 24. Ratio of Pressure Drop of 3/4-In. Standard Packings to New Packing vs. Gas Flow

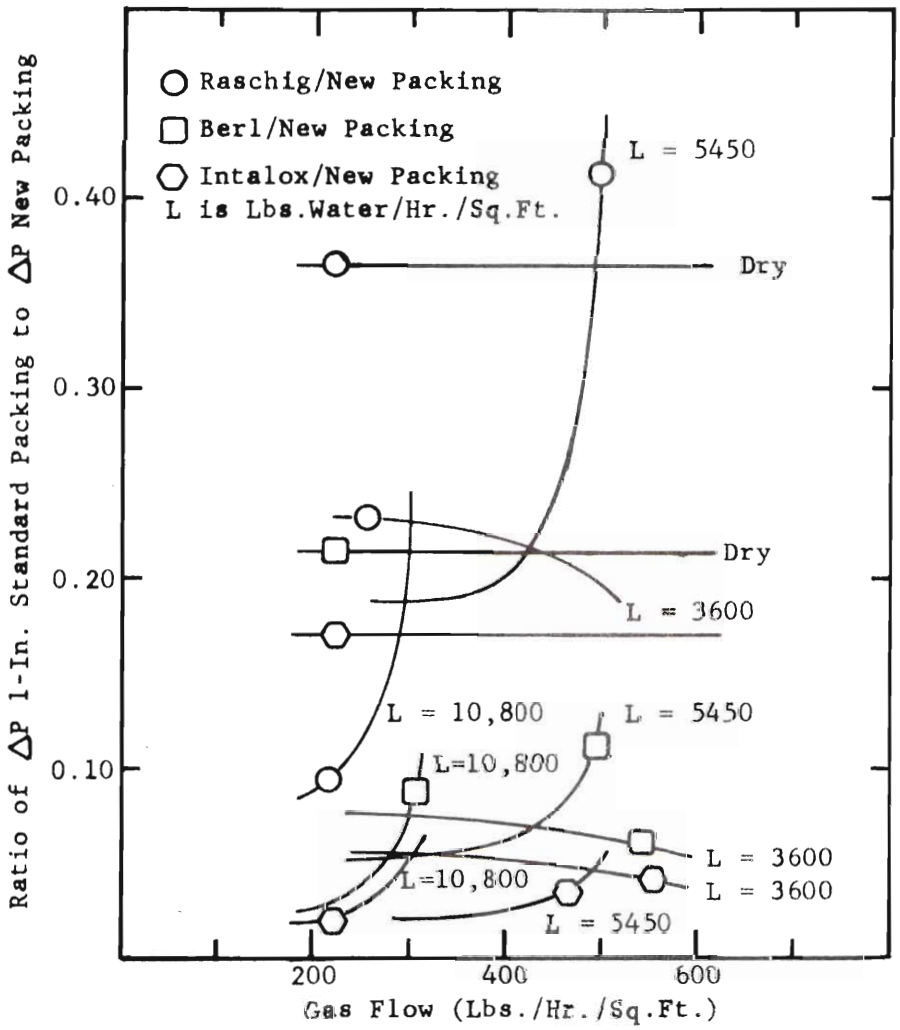


Figure 25. Ratio of Pressure Drop of 1-In. Standard Packing to New Packing vs. Gas Flow

ratios of these 1/2-in. packings increase slowly at first then quite rapidly. The Raschig rings increase from 1.0 to 2.2, the Berl saddles from 0.2 to 0.4 and the Intalox saddles from 0.1 to 0.3, all in the gas flow range of 200 to 500 lbs./hr.-sq.ft. The figures showing the relative pressure drops for 3/4-in. and 1-in. packing to the new packing, indicate that the larger packing offers very much less resistance to flow. For the previously mentioned flows, the pressure drops for 3/4-in. and 1-in. packings are generally 10 to 20 times lower than those for the new packing.

Absorption

The rate of absorption of ammonia from an air-ammonia stream by a counter current flow of water was measured for various air, ammonia, and water flows. The absorption tower was a 3-in. diameter glass pipe filled with two feet of the specially fabricated packing. The ammonia rate was about 0.076 mole ratio or 7 per cent mole per cent in air flows of 127, 190, 253, 317, 380, 443, 537, 570 and 633 lbs./hr.-sq.ft. The water flows were 1558, 3116, 4674 and 6232 lbs./hr.-sq.ft. The actual absorption rates were calculated from the quantity of ammonia found in the water effluent. The values of $K_G a$, the overall absorption coefficient based on the gas phase, H_{OG}, the overall height of one transfer unit, and N_{OG} the number of overall transfer units were then determined for each combination of gas and water flow. These results are tabulated in Table 7. Figure 26 shows the relationship between N_{OG} and air rate for constant water rates. It can be seen that the number of transfer units for this column decreased with increased gas flow and increased with increased water flow for rates below the flooding region.

Table 7. N_{OG}, H_{OG}, K_Ga, for Moebius Rings for Various Gas and Water Rates

Liquid	Gas	N_{OG}	H_{OG}	K_Ga
1558	127	3.87	0.52	8.55
3116	127	4.61	0.43	10.34
4674	127	5.54	0.36	12.35
6232	127	6.02	0.33	13.47
1558	190	3.70	0.54	12.29
3116	190	4.29	0.47	14.12
4674	190	4.83	0.41	16.15
6232	190	5.89	0.34	19.48
1558	253	3.16	0.63	13.99
3116	253	3.42	0.58	15.19
4674	253	4.65	0.43	20.49
6232	253	5.90	0.34	25.87
1558	317	2.62	0.76	14.37
3116	317	3.38	0.59	18.51
4674	317	4.59	0.44	24.81
6232	317	5.37	0.37	29.45
1558	380	2.41	0.83	15.67
3116	380	3.18	0.63	20.63
4674	380	4.34	0.46	28.20
6232	380	5.65	0.35	37.02
1558	443	2.28	0.88	17.04

Table 7. N_{OG}, H_{OG}, K_Ga, for Moebius Rings for Various Gas and Water Rates (Continued)

Liquid	Gas	N_{OG}	H_{OG}	K_Ga
3116	443	3.06	0.65	23.07
4674	443	4.32	0.46	32.56
6232	443	5.25	0.38	39.14
1558	507	2.11	0.95	17.89
3116	507	3.04	0.66	25.70
4674	507	4.72	0.42	40.13
6232	507	5.72	0.35	47.81
1558	570	2.09	0.96	19.71
3116	570	3.13	0.64	29.48
4674	570	4.86	0.41	45.25
6232	570	6.08	0.33	55.86
1558	633	2.36	0.85	24.40
3116	633	3.58	0.56	36.73
4674	633	5.36	0.37	55.35
6232	633	6.77	0.30	67.83

L = Lbs. water/hr.-sq.ft.

G = Lbs. gas/hr.-sq.ft.

N_{OG}= No. of transfer unit

H_{OG}= Height of transfer unit (ft.)

K_Ga= Lb. moles/hr./cu.ft./atm.

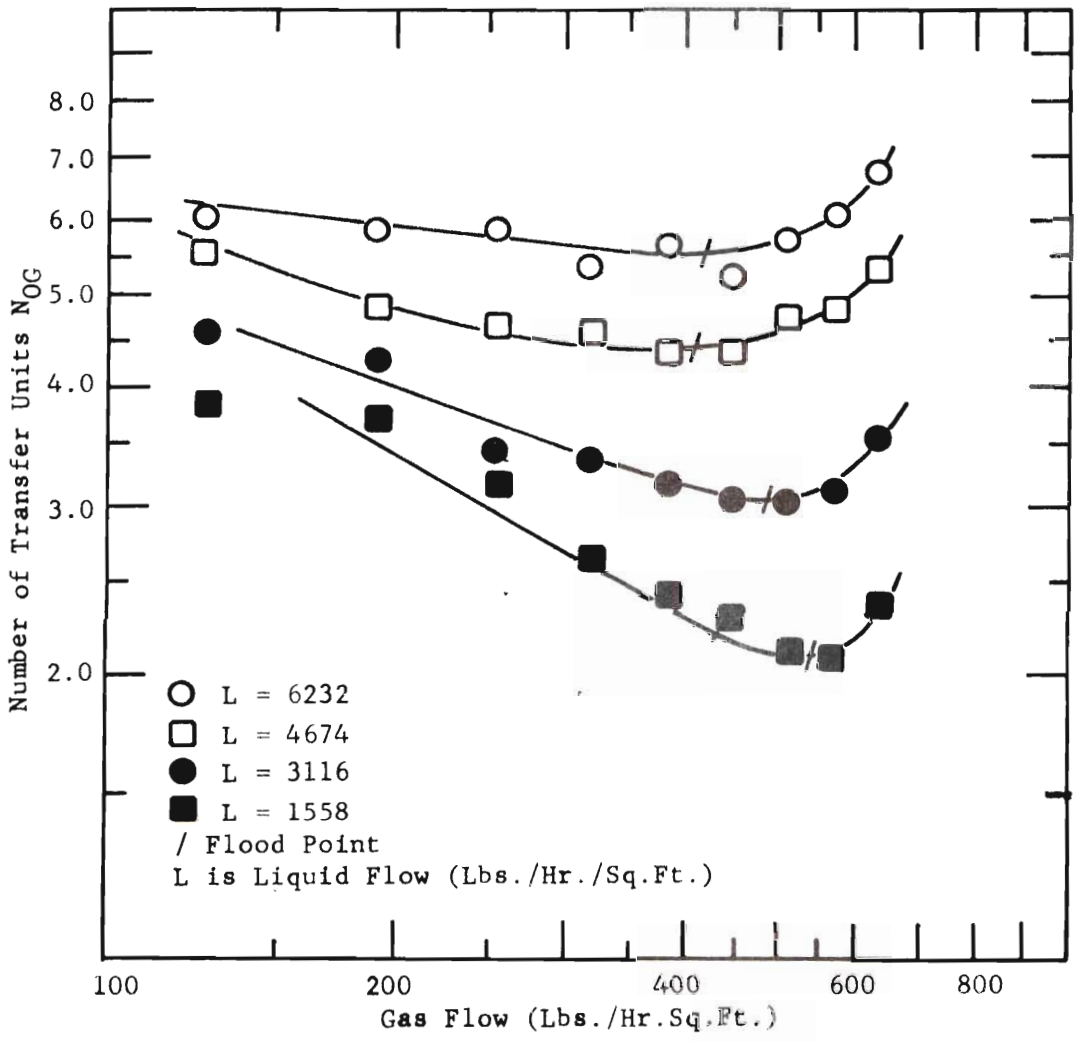


Figure 26. Number of Transfer Units vs. Gas Flow

At air rates of 200 lbs./hr.-sq.ft. and water rates of 6232, 4674, 3116 and 1558, lbs./hr.-sq.ft., N_{OG} equalled about 0.60, 0.47, 0.39 and 0.34, respectively. For an air flow of 400, and the same water rates, the N_{OG}'s were about 0.53, 0.43, 0.31 and 0.23 transfer units, respectively. In Figure 27, we see the relationship of H_{OG} and gas flow at constant water flows. For a water rate of 1558 lbs./hr.-sq.ft., H_{OG} increases from 0.48 to 0.95 feet in the air flow range of 127 to 570 lbs./hr.-sq.ft. At a water rate of 3116, H_{OG} increases from 0.40 to a maximum of 0.66 feet between the air rates of 127 and 480. Similarly, for the water rate of 4674 and an air rate of 127, H_{OG} was found to be 0.36. For the same water rate but with an air rate of 350, H_{OG} increased to 0.46, but at an air rate of 633, H_{OG} had dropped back to 0.37. At the water rate of 6232 lbs./hr.-sq.ft., the maximum H_{OG} of 0.37 was obtained at about 400 lbs. air/hr.-sq.ft. while at 127, and 633 lbs. air/hr.-sq. ft. H_{OG} was 0.32 and 0.30, respectively. The values of H_{OG} reach a maximum at the flooding region then decrease presumably because the increased turbulence enhances absorption. The direct comparison of some H_{OG} values for several other packings is shown in Figures 28 and 29. In Figure 28 H_{OG} versus gas flow is plotted for 3/8-in. Raschig rings, 1/2-in. Raschig rings, 1/2-in. Berl saddles, 1-in. Raschig rings and 1-in. Berl saddles. The water flow was constant at 1500 lbs./hr.-sq. ft. These data were reported by Fellinger (20) who used an 18-in. column and an ammonia concentration of 2 mole per cent. The H_{OG} values for the new packing were plotted on this figure for the water flow of 1558 lbs./hr.sq. ft., the closest results available for comparison.

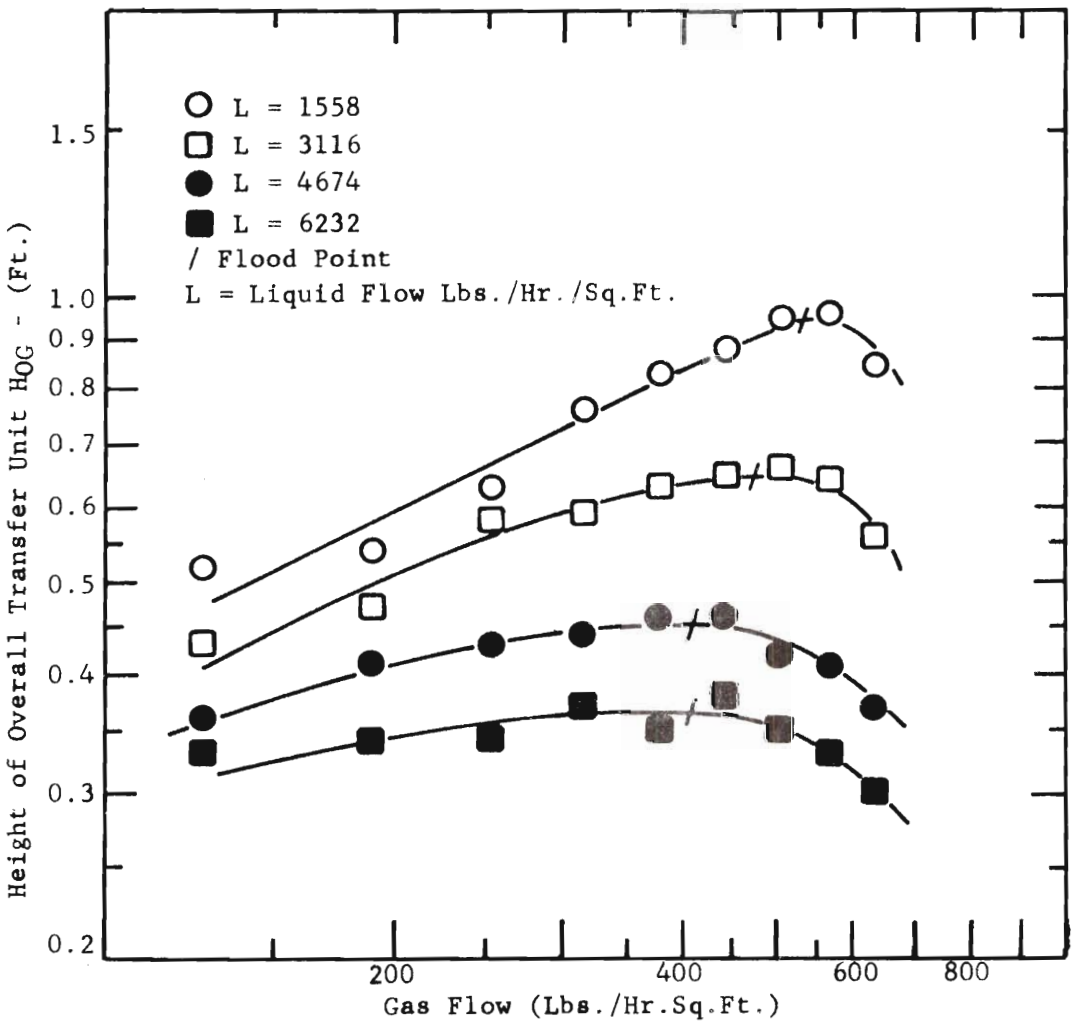


Figure 27. Height of Overall Transfer Unit vs. Gas Flow

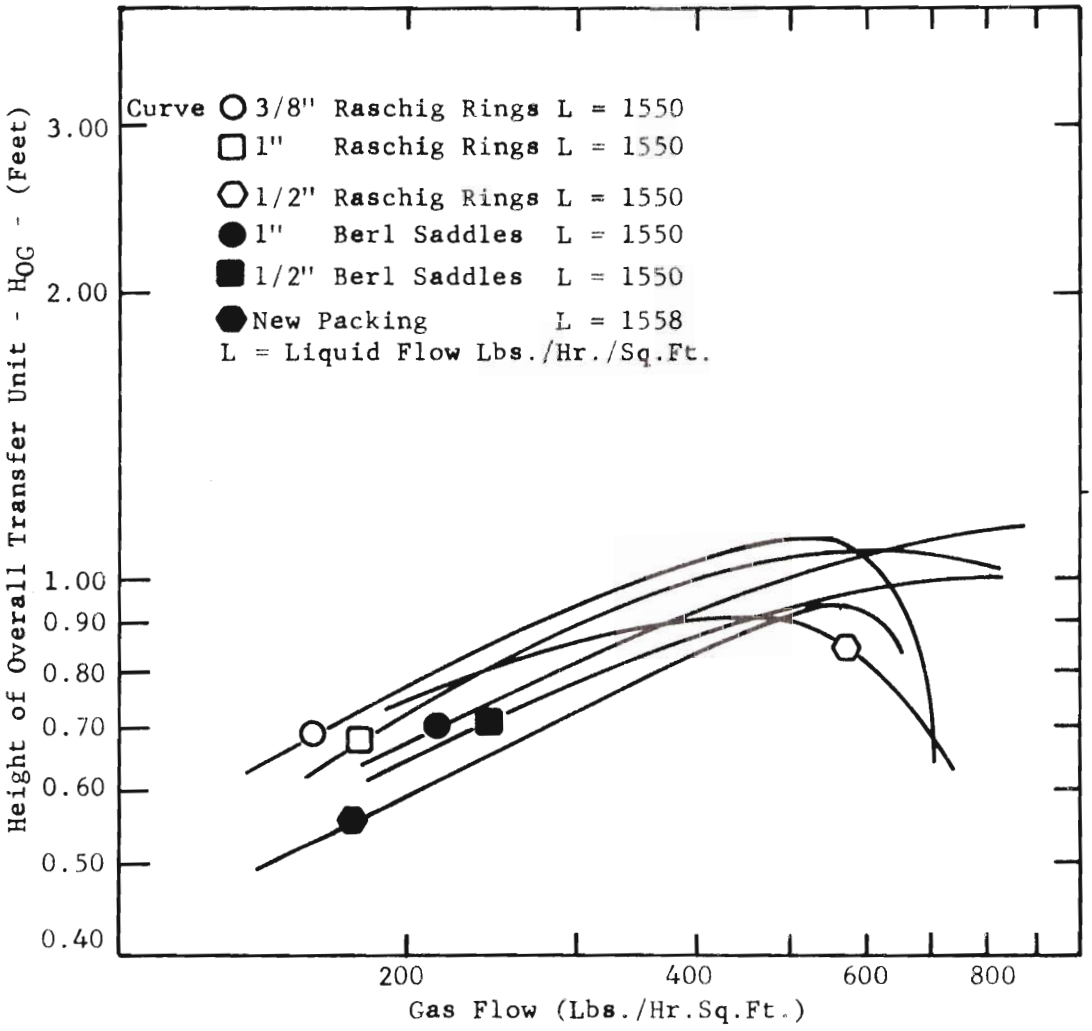


Figure 28. Height of Overall Transfer Unit for Various Packing vs. Gas Flow

These water flows are certainly close enough to allow direct comparison of the H_{OG}'s. The new packing shows the same general trend of H_{OG} versus gas flow as does the 3/8-in. Raschig ring. That is, the H_{OG} for the new packing increases at a certain rate, reaches a maximum and then falls sharply, in the same manner as for the 3/8" Raschig ring. The new packing, however, shows the H_{OG} values to be about 20 per cent lower than the rings. The maximum H_{OG} is 0.95 feet at 570 lbs. air/hr.sq.ft. while for the 3/8-in. rings, the maximum H_{OG} is 1.1 at about 500 lbs. air/hr.-sq.ft. The H_{OG}'s for 1/2-in. Berl saddles are on the average about 2 per cent higher than for the new packing. Therefore, the new packing may be considered to be as efficient as 1/2-in. Berl saddles except that for the saddles, flooding occurs at about 700 lbs. air/hr.-sq.ft. Thus, the new packing is 20 per cent more efficient than 3/8-in. Raschig rings and equal to 1/2-in. Berl saddles at water flows of 1500 lbs./hr.-sq.ft. The efficiency of one-inch Berl saddles, one-inch Raschig rings, and 1/2-in. Raschig rings lie between those of 3/8-in. Raschig rings and 1/2-in Berl saddles.

In Figure 29, Fellinger's (20) data for 3/8-in. Raschig rings, 1/2-in. Raschig rings, 1/2-in. Berl saddles, 1-in. Raschig rings, and 1-in. Berl saddles were plotted to show H_{OG} versus gas flow at a constant water flow of 4500 lbs./hr.-sq.ft. The H_{OG}'s of Intalox saddles were available only for a water flow of 4000 lbs. water/hr.-sq.ft. and for the 1-in. size (26). The closest available data for the new packing was at a water flow of 4674 lbs./hr.-sq.ft. Below the flooding region the new packing is about 80 to 90 per cent more efficient than 3/8-in. Raschig rings. It is also more efficient than 1/2-in. Raschig rings,

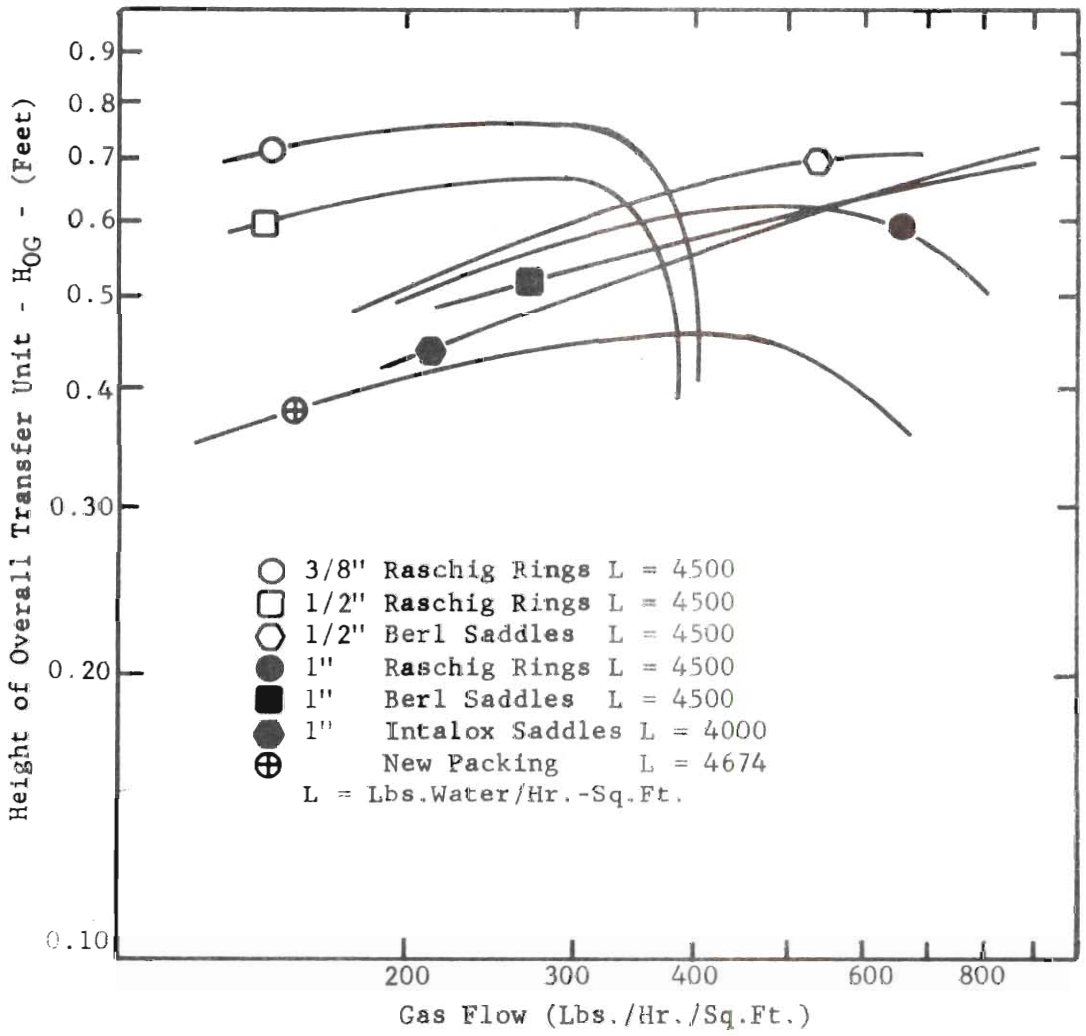


Figure 29. Height of Overall Transfer Unit for Various Packing vs. Gas Flow

1/2-in. Berl saddles, 1-in. Raschig rings, and 1-in. Berl saddles by about 60-65 per cent, 20-25 per cent, 20-25 per cent and 15-20 per cent, respectively. The figure also shows the new packing to be about 5 to 10 per cent more efficient than 1-in. Intalox saddles. It must be remembered, however, that the liquid rate is different in this case. For a liquid flow of 4500 lbs./hr.-sq.ft., one might estimate that 1-in. Intalox saddles and the new packing are comparable.

Figure 30 shows the relationship of the $K_G a$'s with gas flow for the new packing at constant water flows of 1558, 3116, 4674 and 6232 lbs./hr.-sq.ft. The $K_G a$'s are proportional to the 0.43, 0.57, 0.78, and 0.79 powers of the air flow at these water flows, respectively. Above 400 lbs. air/hr. sq.ft., the $K_G a$ increase much more rapidly. Thus, at 200 lbs. air/hr. sq.ft., the $K_G a$'s are 11.5, 14.0, 17.5, and 21.0 lbs. moles/hr. cu.ft.atm., at 1558, 3116, 4674, and 6232 lbs. water/hr.sq.ft., respectively. At 500 lbs. air/hr.sq.ft. and for the same order of water flows the $K_G a$'s are 18.5, 25.5, 37.5, and 46.3 lbs. moles/hr.cu.ft.atm. Again for the same order of water flows, but at 600 lbs. air/hr.sq.ft., the $K_G a$'s sharply increase to 22.0, 31.2, 48.4, and 59.3 lbs. moles/hr. cu.ft.atm., respectively.

Figure 31 compares the $K_G a$'s at 1500 lbs. water/hr.sq.ft. as reported by Fellinger (20) for 3/8-in. Raschig rings, and 1-in. Berl saddles with the $K_G a$'s for the new packing at 1558 lbs. water/hr.sq.ft. Except for air flows above 600 lbs./hr.-sq.ft., the $K_G a$'s for all these packings lie within a spread of 20 per cent. Therefore, the efficiencies of these packings are about equal at 1500 lbs. water/hr.-sq.ft. Since

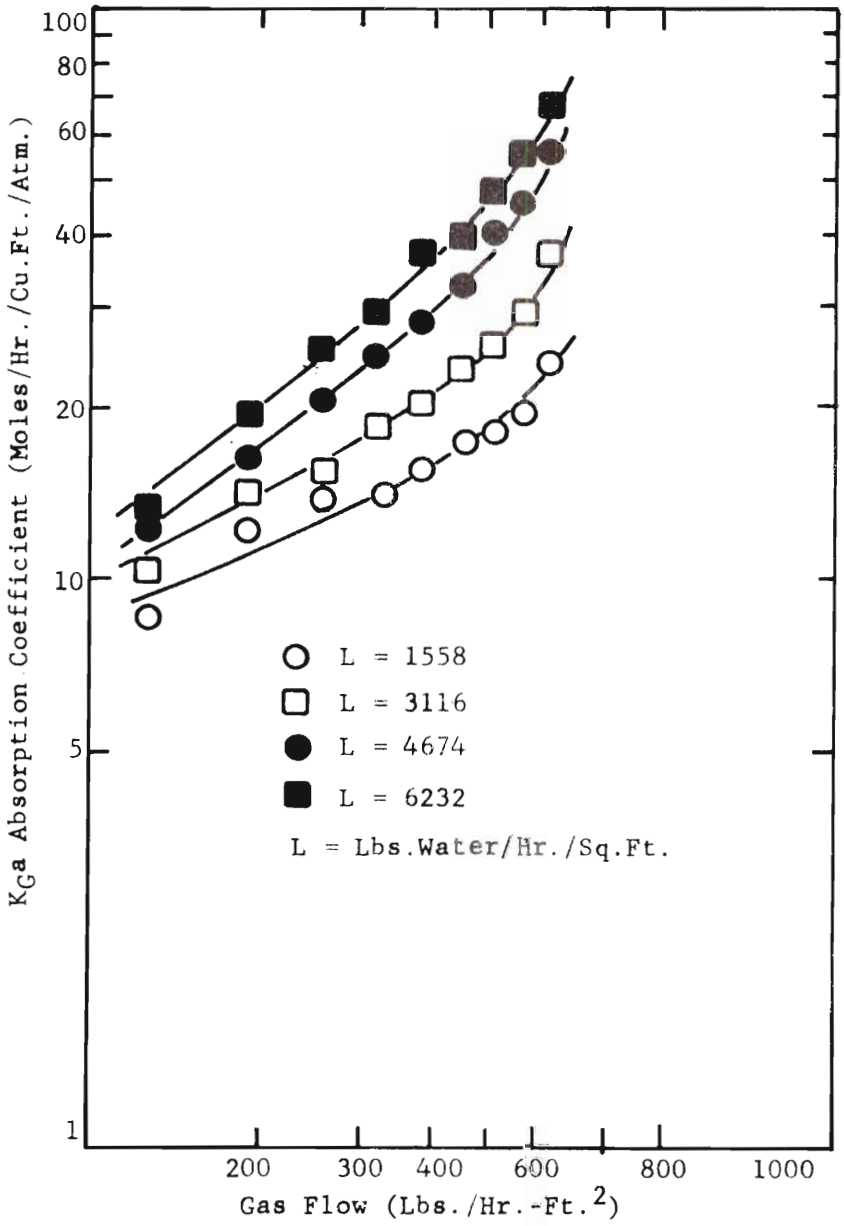


Figure 30. K_Ga for New Packing vs. Gas Flow

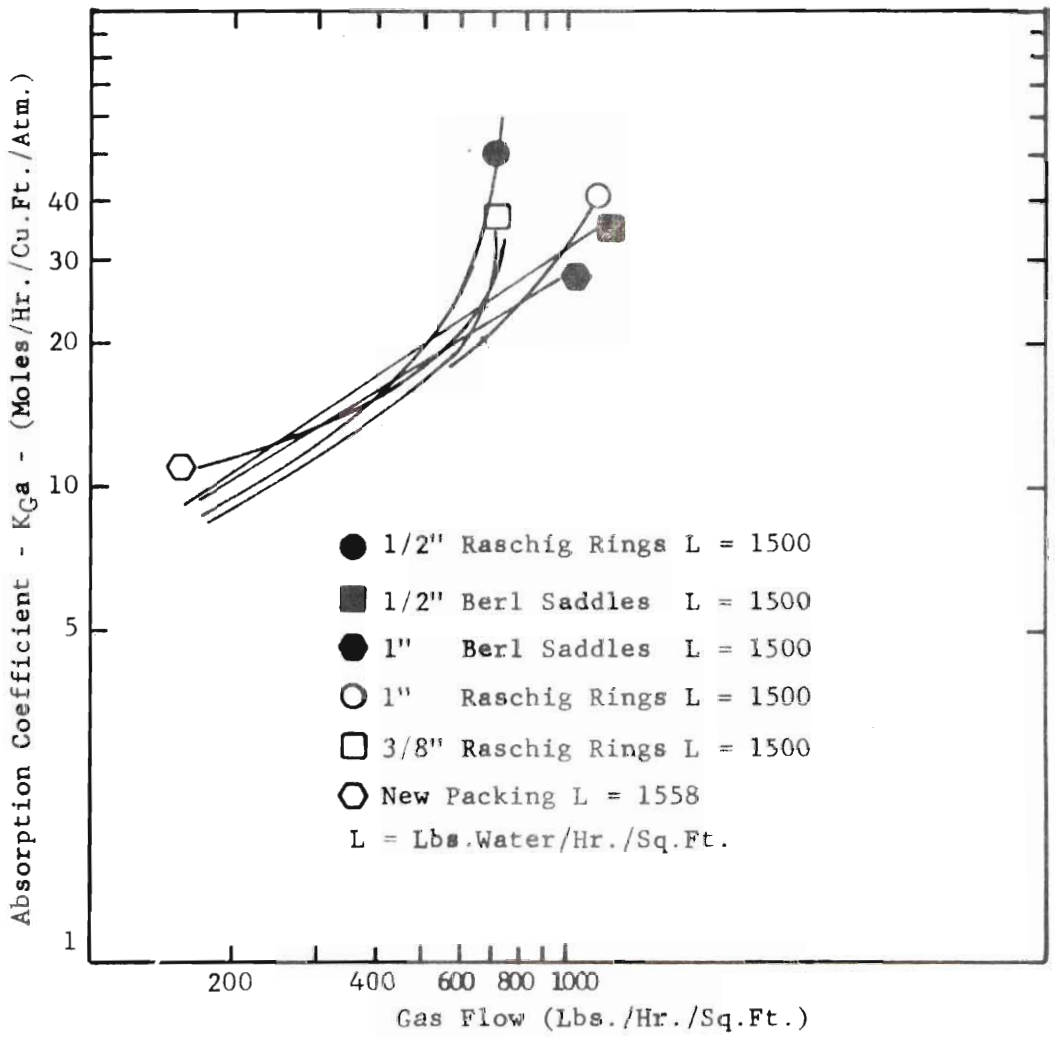


Figure 31. $K_G a$ for Various Packing vs. Gas Flow

the surface area of the new packing, 104 sq.ft./cu.ft., is the lowest of the compared packings, the effective wetting of the new packing must be the highest.

Figure 32 is same as Figure 31 except that the water flow is 4500 lbs./hr.-sq.ft. for all packings except the new one. In this case, the water flow is 4674 lbs./hr.-sq.ft. The values for $K_G a$'s are bunched in three groups. The new packing is in one group by itself, 1/2-in. Berl saddles, 1-in. Berl saddles and 1-in. Raschig rings make up the second group, while 3/8-in. and 1/2-in. Raschig rings make up the third. The second and third groups show values of $K_G a$ about 22 per cent and 39 per cent, respectively, less than those of the new packing. For the higher water rate the new packing is evidently more efficient than the compared packings. These data indicate again the higher effectiveness of wetting of the new packing.

Generally, the results for the new packing show relatively good absorption. The pressure drops, however, present an interesting result. The pressure drop across a bed of non-irrigated packing of Moebius rings shows an excellent correlation with the Carmen equation as shown in Appendix 11. When the bed is irrigated with water, the pressure drops at liquid flows above about 6000 lbs./hr.-sq.ft., follow the results expected according to the correction factors of Sherwood and Pigford presented in Appendix 11. For lower liquid rates the pressure drops are much higher than expected.

In an attempt to explain this phenomenon the static and operating holdups were determined. The data are presented in Appendices 9 and 10. Although the operating holdup followed the relationship established for

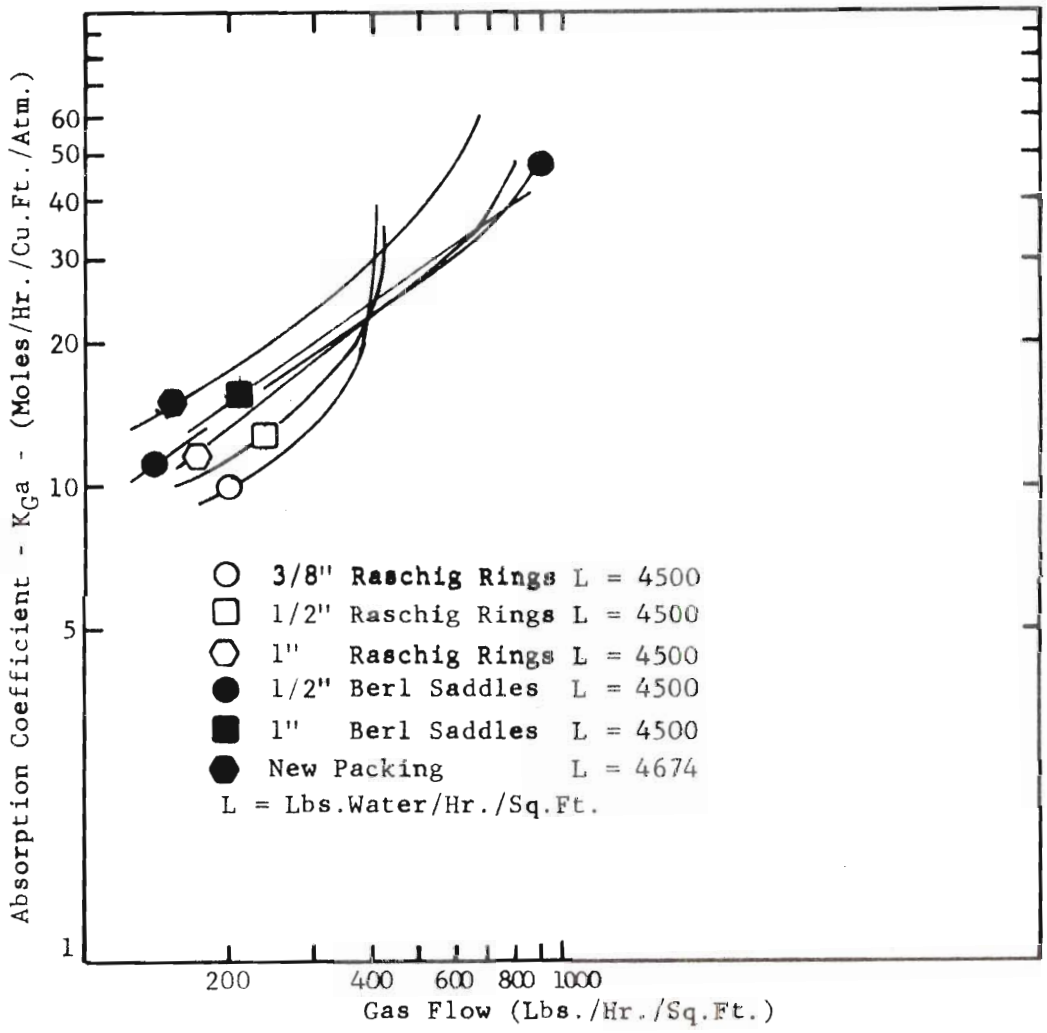


Figure 32. K_Ga for Various Packing vs. Gas Flow

other packings, the static holdup did not (30, 31). The static holdup of 0.0633 cu.ft. water/cu.ft. tower, was approximately double that reported for Raschig rings or Berl saddles.

These high pressure drops for low liquid rates might be explained as follows: The high static holdup evidently blocks the small internal spaces of the moebius rings. All the liquid rates measured fall in the transition region. At the lower rates the blockage is high. At the higher liquid rates liquid turbulence helps to open up some of these "dead spaces." Consequently, these spaces become available to gas flow. The pressure drop then becomes more dependent on the operating holdup and follows more nearly the expected result.

Accuracy of Results

The pressure drop measurements were reproducible to 0.01 units. With the water manometer the units were inches of water and with the mercury manometer the units were in inches of mercury. The error in pressure drop across the packing is therefore as high as 20 per cent at the lowest pressure drop and decreases to a low of 0.5 per cent for the high pressure drops.

The accuracy of the number of transfer units, the height per overall transfer unit and the absorption coefficients, depends primarily upon the measurement of the concentration of the water effluent. This maximum deviation of this measurement was found to be 5 per cent. By differentiating the absorption equation the maximum error of N_{OG}, the number of transfer units, was found to be 10 per cent. Similarly, H_{OG}, the height of overall transfer unit, and $K_G a$ the absorption coefficient, showed maximum errors of 10 per cent.

CHAPTER V

CONCLUSIONS

An attempt was made to fabricate a new type of packing with the shape of a moebius ring. The ring had the dimension 1/2-in. high, 1/2-in. effective diameter and 3/32-in. wall thickness. The usefulness of this ring as a packing was determined by packing a 3-in. column with the rings, measuring the pressure drop at several air and water flows, and evaluating the efficiency of the packing when used in an air-ammonia-water absorption column. From the results of the evaluations the following conclusions were drawn.

A packing with a shape similar to a moebius ring can be mass produced by the Ram process or by pressing techniques similar to those applied to the fabrication of Berl or Intalox saddles.

A tower packed with 1/2-in. moebius rings contained 9000 rings per cubic foot, had a surface area of 104 square feet per cubic foot and a void space of 63 per cent.

For this tower the flooding region occurred at a pressure drop from 4.6 to 4.8 inches of water per foot of packing. Over this range the water flow varied from 10,945 to 4,900 pounds per hour per square foot, and the air flow varied from 380 to 640 pounds per hour per square foot. The pressure drop at flooding was about 34 per cent higher than across a tower packed with 1/2-in. ceramic Raschig rings. Below the flooding region the pressure drop across moebius rings was

proportional to the 1.9 power of the gas flow. The proportionality decreased to the 1.6 power of the gas flow as the constant water flow parameter increased from 1225 to 10,945 lbs./hr.-sq.ft.

When operating at water rates from 3600 to 5350 lbs./hr.-sq.ft. and at air rates from 200 to 500 lbs./hr.-sq.ft., the pressure drop across the moebius packing was 25 per cent more to 45 per cent less, 12 to 17 per cent more, and 11 to 14 per cent more than across a tower packed with 1/2-in. ceramic Raschig rings, Berl saddles and Intalox saddles, respectively.

For a column packed with 3/4-in. or 1-in. Raschig rings, Berl saddles, or Intalox saddles, the pressure drop was 10 to 20 times lower than for the column packed with 1/2-in. moebius rings.

When used as a packing in the absorption of ammonia from air with water the height of the overall transfer unit, H_{OG}, for the moebius rings decreased with increased water ratio, and increased slowly with increased gas flow up to the flooding region. Above flooding, H_{OG} rapidly decreased.

Below the flooding region and at low water rates, Berl saddles, Raschig rings and Intalox saddles ranging in size from 3/8-in. to 1-in. gave H_{OG} values which were only slightly higher than the H_{OG}'s of moebius rings. At higher water flows the H_{OG}'s of the standard packings were as much as 85 per cent higher than the H_{OG}'s of moebius rings.

At constant water flows the $K_G a$'s for moebius rings were proportional to a certain power of the air flow. This power increased from 0.43 to 0.79 as the water flow parameter increased from 1558 to 6232

lbs./hr.-sq.ft. The K_Ga's of the standard 1/2-in. packing and the moebius ring were equal within a 10 per cent variation for the low water flows. For a water flow of 4500 lbs./hr.-sq.ft., the K_Ga's of the standard 1/2-in. packing were 20 to 40 per cent lower than the K_Ga's of the moebius rings.

Although the absorption coefficients for moebius rings were equal to or better than the K_Ga's of the investigated standard packing, the pressure drops across the packing at low liquid rates were considerably higher than anticipated. The small internal spaces of the 1/2-in. moebius ring apparently become blocked at low liquid flows. This cuts down on the space available for gas flow, thus creating high pressure drops.

CHAPTER VI

RECOMMENDATIONS

Since a practical method of fabricating moebius rings has been established, any number or size of rings may be simply and quickly produced. It is suggested therefore that the 1/2-in. moebius rings be evaluated when used as a packing in a column of 20 inches in diameter or larger. Such an evaluation would be more meaningful to industry since 3-in. diameter columns are seldom used. For the same reason, one should also consider the evaluation of moebius rings with height and diameter as large as two inches.

To further determine the effect of the physical dimensions of the moebius ring on its value as a packing, rings could be fabricated such that the ratios of effective diameter to height were larger than one to one. A ring with a ratio of three to one, for example, might exhibit a very open structure that could not support appreciable liquid holdup. The result could produce the desirable low pressure drops across such packing.

If further experiments are carried out with any new packing, it would be very advantageous to carry out the same experiments on a thoroughly investigated standard packing. This would allow one to compare all results directly.

One might also correct for end effects in the column by carrying out all experiments at several packing heights. The results could

then be extrapolated to zero height to determine the correction factor.

A P P E N D I X

APPENDIX I

CAPACITY OF PACKED TOWERS

Consider the steady state operation of a countercurrent gas-liquid absorption tower. The gas phase consists of two components: an inert gas which contains a concentration of solute gas. This concentration may be expressed in terms of moles of solute gas per mole of inert gas. The liquid phase also consists of two components: a liquid solvent in which is dissolved a concentration of the solute gas. In this case the concentration may be expressed in terms of moles of solute gas per mole of solute free liquid.

The liquid phase is introduced at the top of the tower, flows down through it and escapes at the bottom, while the gas phase is introduced at the bottom, rises through the column and escapes from the top.

Let us define the following terms:

N = rate of mass transfer through unit area of interface. (lb.moles/hr.-sq.ft.)

k_g = gas-film coefficient. (lb.moles/hr.-sq.ft.-atm.)

P_g = partial pressure of dissolved gas in gas phase. (atm.)

P_i = partial pressure of dissolved gas at interface. (atm.)

P_e = partial pressure of solute over a solution with the composition of the main liquid stream. (atm)

K_G = overall coefficient. (lb.moles/hr.-sq.ft.-atm.)

Z = total height of packed section of tower. (ft.)

S = cross-sectional area of tower. (sq.ft.)

a = interfacial area per unit volume of the column. (sq.ft./cu.ft.)

G = moles of inert gas per unit time per unit cross section of tower. (lb.moles/hr.-sq.ft.)

L = moles of solute-free liquor per unit time per unit cross section of tower. (lb.moles/hr.-sq.ft.)

X = concentration of solute gas in liquid phase. (Moles of solute gas per mole of solute-free liquid)

Y = concentration of solute gas in gas phase. (Moles of solute gas per mole of inert gas)

Subscripts B and T designate conditions at bottom and top of tower, respectively.

Therefore,

$$N = k_g(P_g - P_i)$$

defines the rate of transfer of material through the gas film. This equation, however, is not very practical since neither k_g nor P_i may be easily determined. It is, therefore, advantageous to use an overall coefficient K_G which is defined by the equation:

$$N = K_G(P_g - P_e)$$

If the gas is very soluble, then the resistance to mass transfer is predominantly in the gas film. In this case the liquid film contributes very little to the overall resistance. Therefore, one may use the above equation to determine transfer of material from the gas phase to the liquid phase.

Consider any plane at which the mole ratios of solute in the gas and liquid phases are Y and X. Over a small height dZ, the moles taken up by the liquid will equal the moles leaving the gas. The change of concentrations over the height dZ will be dY and dX in the gas and liquid phases, respectively. Therefore,

$$SGdY = SLdX$$

and the total interfacial area for transfer in the height dZ of a column is a SdZ. Multiplying both sides of the rate equation,

$$N = K_G(P_g - P_e)$$

by a SdZ, one obtains

$$NaSdZ = K_G(P_g - P_e)aSdZ$$

Either side of the equation expresses the total mass transfer over a height dZ. The moles of solute leaving the gas phase are, however, equal to the total mass transfer. Therefore,

$$SGdY = NaSdZ = K_G(P_g - P_e)aSdZ$$

and,

$$GdY = K_G(P_g - P_e)adZ$$

Since the term a is not known, it is convenient to combine the overall coefficient K_G with this term. The product K_Ga is then determined experimentally as one coefficient. Further, since

$$P_g = \frac{Y}{1 + Y} P$$

and,

$$P_e = \frac{Y_e}{1 + Y_e} P$$

where P is the total average pressure of the gas phase, in atmospheres therefore,

$$GdY = K_GaP \left[\frac{Y}{1 + Y} - \frac{Y_e}{1 + Y_e} \right] dZ$$

If we introduce a factor $\emptyset$ (25) such that,

$$\emptyset Y = \frac{Y}{1 + Y}$$

and,

$$\emptyset Y_e = \frac{Y_e}{1 + Y_e}$$

then,

$$GdY = K_G aP\emptyset \ (Y-Y_e)dZ$$

The total height of the tower then becomes,

$$Z = \int_0^Z dZ = \frac{G}{K_G aP\emptyset} \int_{Y_B}^{Y_T} \frac{dY}{Y - Y_e}$$

if the gas film offers essentially all the resistance to mass diffusion. Although the value of $\emptyset$ may change slightly over the column, an average value will generally be sufficiently accurate. It is, therefore, considered to be a constant in the integrated equation. To solve the right hand side of above equation, one must usually rely upon graphical integration. The values of Y may be determined from a material balance on the solute from the bottom, or top, of the column to any plane where the mole ratios are Y and X. Thus,

$$G(Y_B-Y) = L(X_B-X)$$

or,

$$G(Y-Y_T) = L(X-X_T)$$

The values of Y_e are obtained from the equilibrium relationship of the gas phase in equilibrium with the liquid phase. If this equilibrium relationship of Y_e versus X_e is nearly a straight line then one may integrate the above equation by means of the log mean average. Therefore,

$$Z = \frac{G}{K_G aP} \frac{1}{\emptyset} \left[\frac{(Y_B-Y_T)}{(Y-Y_e)_B-(Y-Y_e)_T} \right] \ln \left[\frac{(Y-Y_e)_B}{(Y-Y_e)_T} \right]$$

It is convenient to express the height of the column as the product of the number of overall gas transfer units, N_{OG}, and the height of one transfer unit H_{OG}. Thus,

$$Z = N_{OG} H_{OG}$$

where

$$H_{OG} = \frac{G}{K_G aP}$$

or,

$$K_G a = \frac{G}{H_{OG} P}$$

and,

$$N_{OG} = \frac{1}{\phi} \int_{Y_B}^{Y_T} \frac{dY}{Y-Y_e}$$

$$= \frac{1}{\phi} \frac{(Y_B-Y_T)}{(Y-Y_e)_B-(Y-Y_e)_T} \ln \frac{(Y-Y_e)_B}{(Y-Y_e)_T}$$

N_{OG} is the integrated value of the change in composition per unit driving force, and, therefore, represents the difficulty of the separation.

APPENDIX 2

In this appendix are presented curves showing the calibration of the various florators used in this work. Figure 33 shows the calibration of the florator for ammonia flow. Figures 34, 35, and 36 show the calibration of the florators used to determine air rates, water flow for pressure drop measurements, and water flow for absorption measurements, respectively.

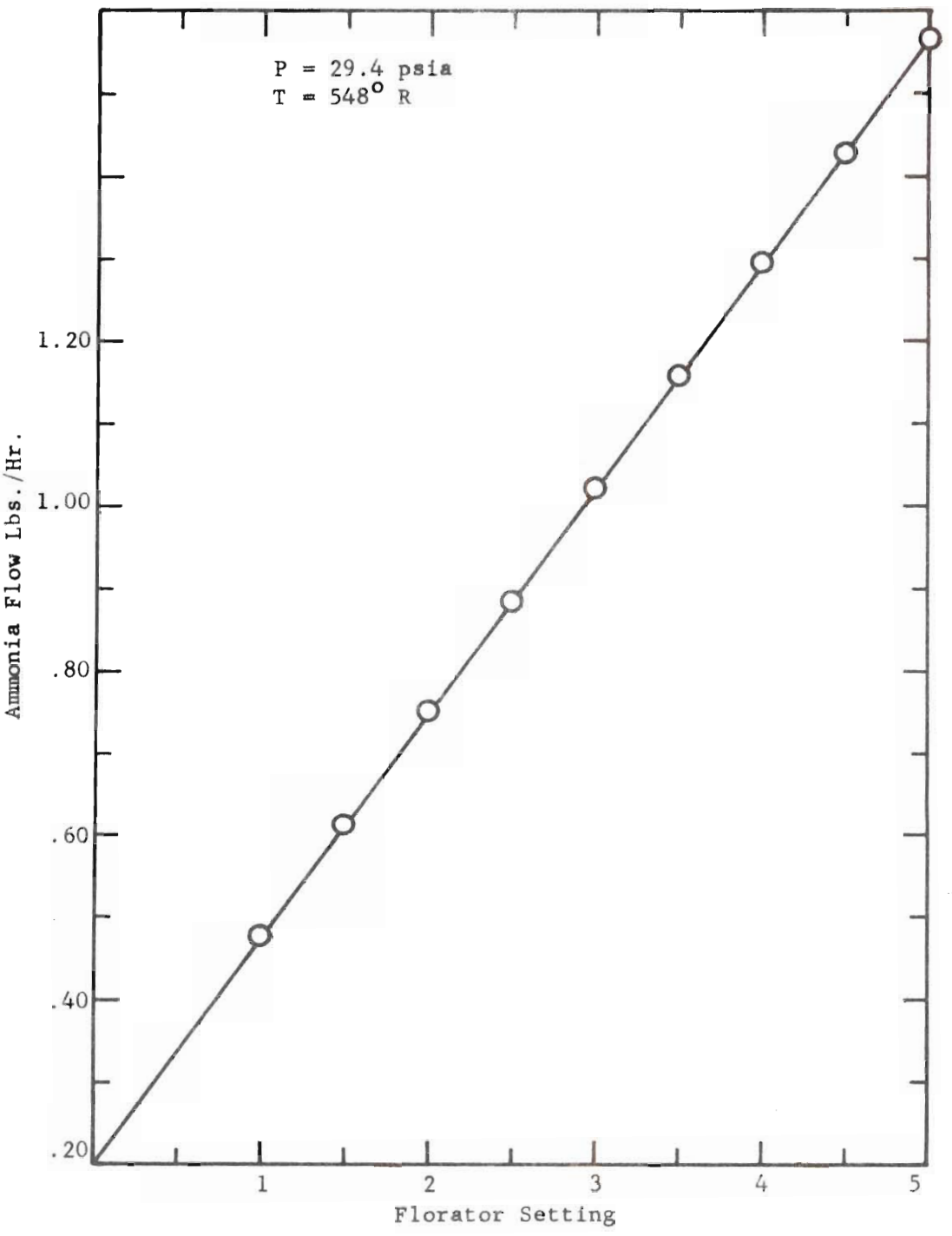


Figure 33. Calibration of Florator Used to Set Ammonia Flow

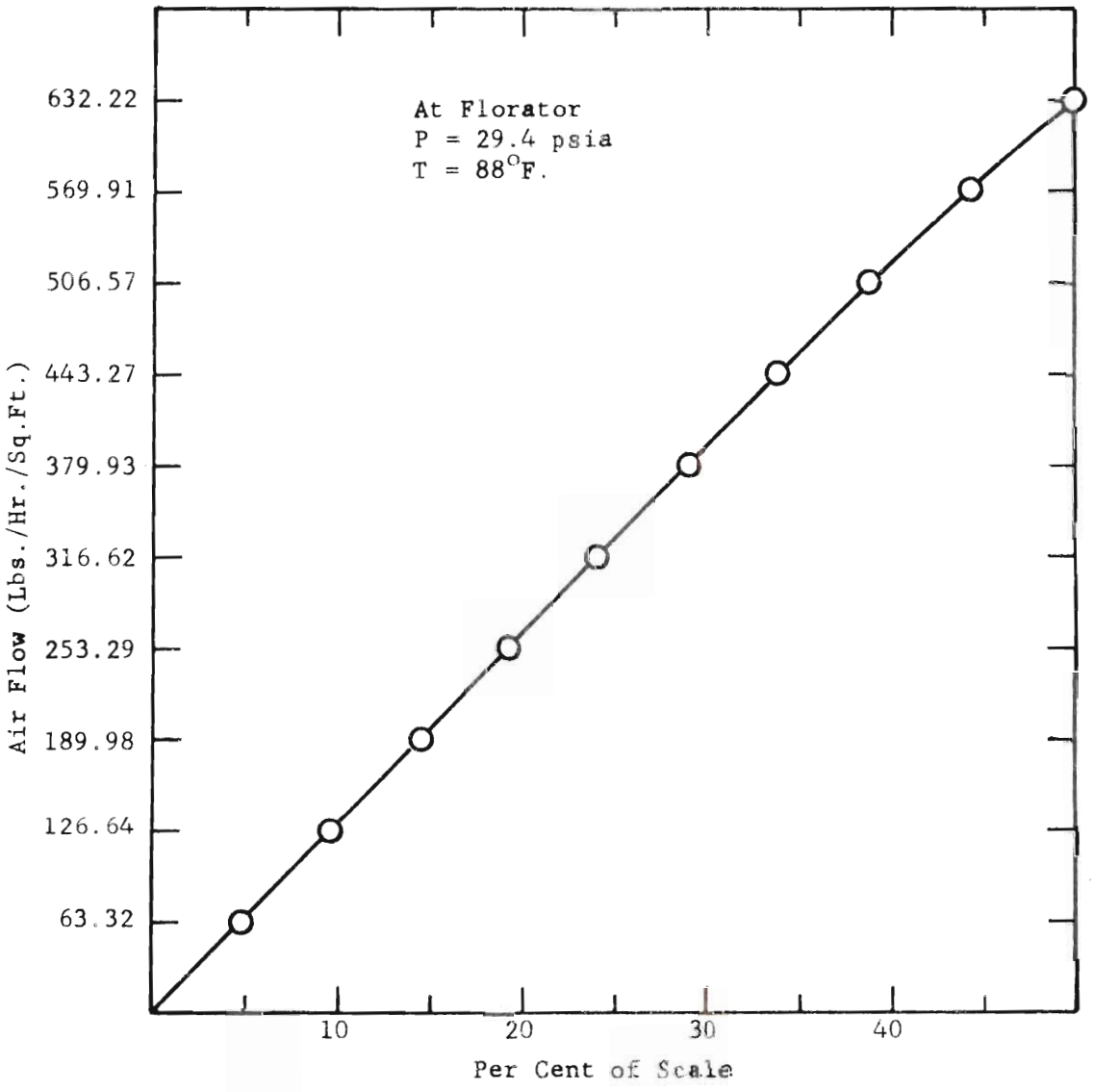


Figure 34. Calibration of Florator Used to Set Air Flow

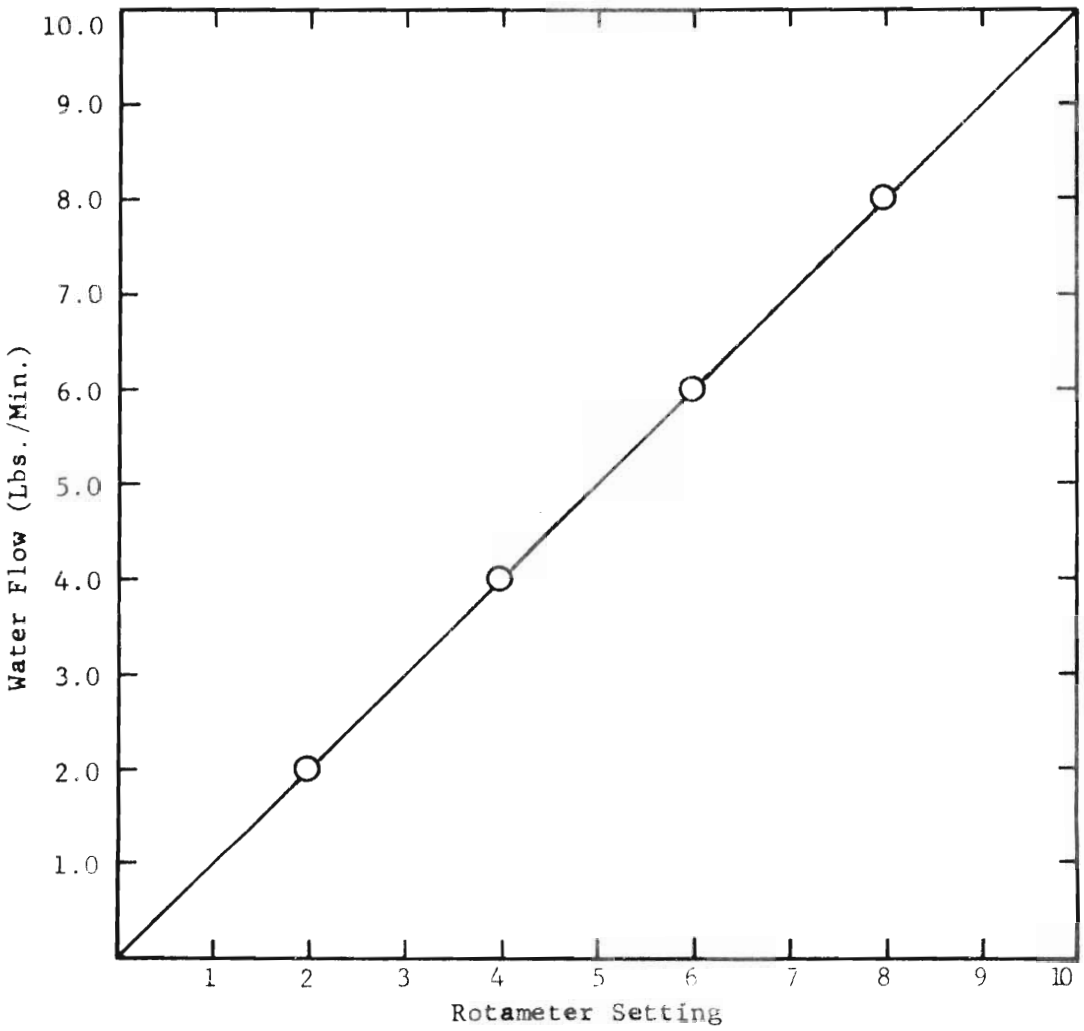


Figure 35. Calibration of Rotameter Used to Set Water Flow Rate for Pressure Drop Measurements

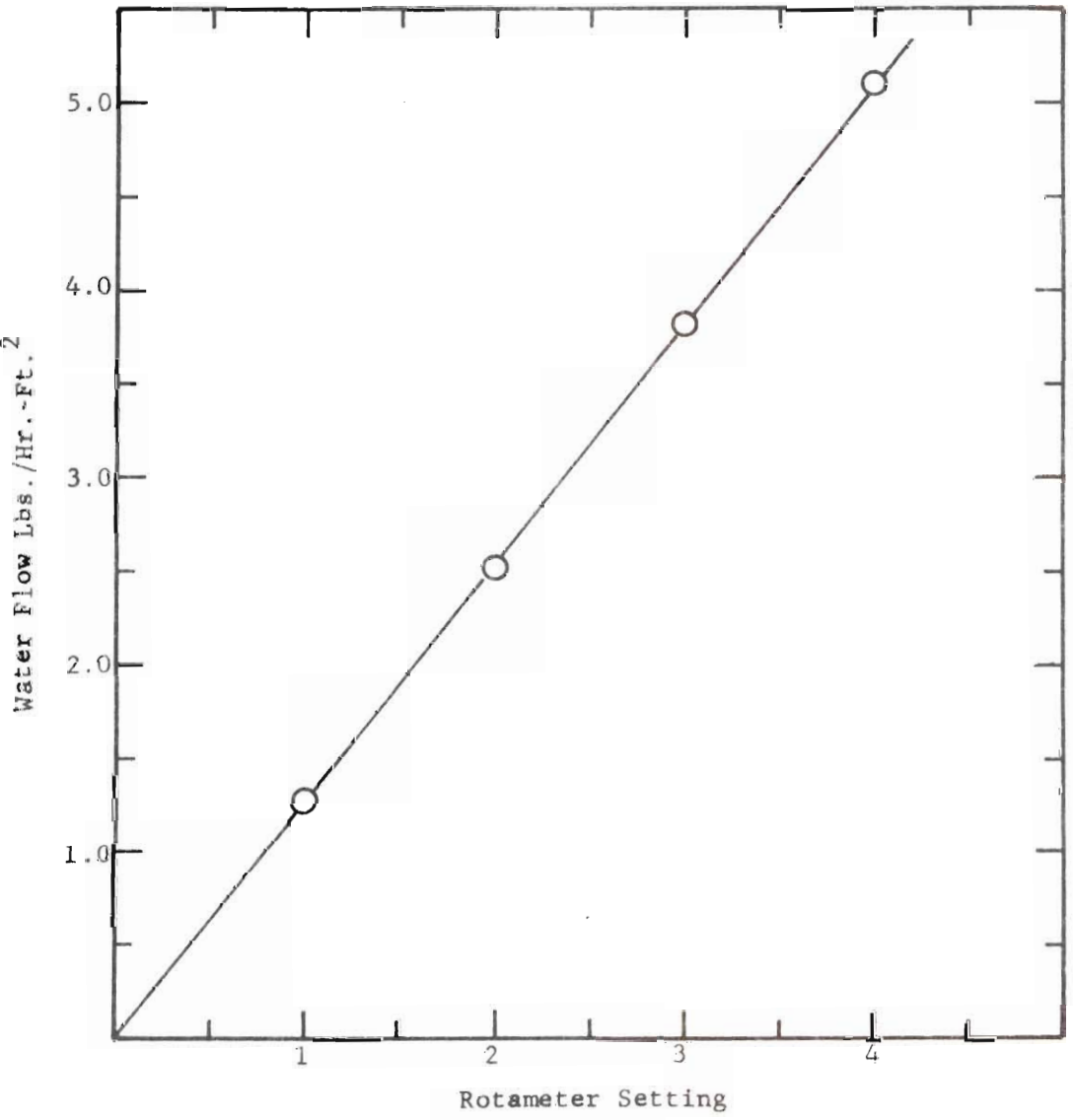


Figure 36. Calibration of Rotameter Used to Set Water Flow Rates for Absorption Measurements

APPENDIX 3

PRESSURE DROP DATA

Table 8. Pressure Drop Across Air-Water Column

Water flow = zero; no packing in column.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	0.68	0.65	0.67	0.68	0.67	in. water
126.64	2.48	2.47	2.49	2.51	2.49	
189.98	5.36	5.33	5.35	5.37	5.35	
253.29	9.21	9.20	9.23	9.24	9.22	
316.62	14.19	14.17	14.21	14.23	14.20	
379.93	1.47	1.45	1.47	1.48	1.47	in. Hg.
443.27	1.98	1.97	1.98	2.00	1.98	
506.57	2.55	2.53	2.54	2.58	2.55	
569.91	3.16	3.13	3.16	3.18	3.16	
633.22	3.89	3.88	3.91	3.92	3.90	

Table 9. Pressure Drop Across Air-Water Column

Water flow = zero; dry packing 4.5 feet.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32						
126.64	2.56	2.57	2.58	2.56	2.57	in. water
189.98	5.50	5.51	5.50	5.50	5.50	
253.29	9.46	9.47	9.47	9.47	9.47	
316.62	14.57	14.57	14.57	14.57	14.57	
379.93	1.51	1.51	1.51	1.49	1.57	in. Hg.
443.27	2.02	2.03	2.03	2.03	2.03	
506.57	2.62	2.62	2.62	2.62	2.62	
569.91	3.24	3.23	3.23	3.25	3.24	
633.22	4.00	3.99	4.00	4.00	4.00	

Table 10. Pressure Drop Across Air-Water Column

Water flow = zero; 4.5 feet packing; wet and drained.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32						
126.64	2.60	2.61	2.60	2.59	2.60	in. water
189.98	5.58	5.59	5.58	5.58	5.58	
253.29	9.60	9.59	9.60	9.61	9.60	
316.62	14.74	14.75	14.76	14.75	14.75	
379.93	1.52	1.54	1 53	1.53	1.53	in. Hg.
443.27	2.06	2.06	2.05	2.06	2.06	
506.57	2.65	2.64	2.65	2.65	2.65	
569.91	3.28	3.29	3.27	3.28	3.29	
633.22	4.04	4.05	4.05	4.06	4.05	

Table 11. Pressure Drop Across Air-Water Column

Water flow = 1225 lbs./hr.sq.ft.; 4.5 feet packing.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	0.73	0.74	0.73	0.72	0.73	in. water
126.64	2.69	2.70	2.70	2.70	2.70	
189.98	5.81	5.81	5.79	5.79	5.80	
253.29	10.09	10.07	10.08	10.08	10.08	
316.62	15 50	15.51	15.51	15.51	15.51	
379.93	1.59	1.58	1.59	1.60	1.59	in. Hg.
443.27	2.17	2.19	2.18	2.18	2.18	
506.57	2.84	2.83	2.83	2.84	2.84	
569.91	3.55	3.56	3.57	3.55	3.56	
633.22	4.43	4.43	4.43	4.42	4.43	

Table 12. Pressure Drop Across Air-Water Column

Water flow = 3675 lbs./hr.sq.ft.; 4.5 feet packing.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	0.73	0.74	0.73	0.72	0.73	in. water
126.64	2.69	2.70	2.70	2.70	2.70	
189.98	5.81	5.81	5.79	5.79	5.80	
253.29	10.09	10.07	10.08	10.08	10.08	
316.62	15.50	15.51	15.51	15.51	15.51	
379.93	1.59	1.58	1.59	1.60	1.59	in. Hg.
443.27	2.17	2.19	2.18	2.18	2.18	
506.57	2.84	2.83	2.83	2.84	2.84	
569.91	3.55	3.56	3.57	3.55	3.56	
633.22	4.43	4.43	4.43	4.42	4.43	

Table 13. Pressure Drop Across Air-Water Column

Water flow = 4900 lbs./hr.sq.ft.; 4.5 feet packing.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	0.77	0.77	0.76	0.76	0.77	in. water
126.64	2.83	2.84	2.84	2.84	2.84	
189.98	6.04	6.05	6.06	6.05	6.05	
253.29	10.53	10.53	10.52	10.53	10.53	
316.62	16.23	16.22	16.23	16.23	16.23	
379.93	1.67	1.66	1.67	1.67	1.67	in. Hg.
443.27	2.27	2.26	2.27	2.27	2.27	
506.57	2.98	2.98	2.99	2.99	2.99	
569.91	4.72	4.72	4.71	4.72	4.72	
633.22						

Table 14. Pressure Drop Across Air-Water Column

Water flow = 6125 lbs./hr.sq.ft.; 4.5 feet packing.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	0.77	0.79	0.78	0.78	0.78	in. water
126.64	2.90	2.90	2.90	2.90	2.90	
189.98	6.22	6.21	6.21	6.20	6.21	
253.29	10.81	10.81	10.79	10.79	10.80	
316.62	16.69	16.68	16.67	16.67	16.68	
379.93	1.73	1.73	1.73	1.72	1.73	in. Hg.
443.27	2.32	2.32	2.33	2.33	2.33	
506.57	3.44	3.45	3.43	3.44	3.44	
569.91						
633.22						

Table 15. Pressure Drop Across Air-Water Column

Water flow = 7810 lbs./hr.sq.ft.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	0.88	0.88	0.88	0.88	0.88	in. water
126.64	3.13	3.14	3.14	3.14	3.14	
189.98	6.54	6.53	6.55	6.54	6.54	
253.29	11.20	11.19	11.19	11.21	11.20	
316.62	17.13	17.13	17.13	17.12	17.13	
379.93	1.81	1.83	1.82	1.81	1.82	in. Hg.
443.27	2.48	2.47	2.49	2.48	2.48	
506.57						
569.91						
633.22						

Table 16. Pressure Drop Across Air-Water Column

Water flow = 9371 lbs./hr.sq.ft.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	0.94	0.96	0.96	0.97	0.96	in. water
126.64	3.37	3.35	3.36	3.36	3.36	
189.98	6.93	6.93	6.93	6.93	6.93	
253.29	11.91	11.91	11.93	11.93	11.92	
316.62	18.12	18.13	18.11	18.12	18 12	
379.93	1.93	1.93	1.94	1.93	1.93	in. Hg.
443.27	2.87	2.88	2.88	2.88	2.88	
506.57						

Table 17. Pressure Drop Across Air-Water Column

Water flow = 10,945 lbs./hr.sq.ft.

Air Flow	PRESSURE DROP					
Lbs./hr.sq.ft.	Series 1	Series 2	Series 3	Series 4	Average	
63.32	1.03	1.02	1.02	1.04	1.03	in. water
126.64	3.56	3.57	3.57	3.58	3.57	
189.98	7.33	7.33	7.32	7.33	7.33	
253.29	12.28	12.27	12.28	12.28	12.28	
316.62	20.32	20.32	20.32	20.31	20.32	
379.93	2.60	2.59	2.60	2.60	2.60	
443.27						

APPENDIX 4

ABSORPTION DATA

Water temperature in = 88°F.
Ammonia plus air in = 88°F.
Ammonia plus air out = 88°F.
Height of packing = 2.0 feet.
Tower pressure = atmospheric pressure plus one-half pressure drop. The manometer was set up to read this.

After one-half hour at set conditions and constant temperature, four samples of water effluent, 50.0 ml. each, were pipetted into 100.0 ml. of 0.5800 N HCl. This solution was back titrated with 0.4882 N NaOH.

Ammonia Flow Lbs./hr.	Water Flow Lbs./hr.sq.ft.	Air Flow Lbs./hr.sq.ft.	Ml. of NaOH for Back-Titration				Average Ml.	Temperature Water Out °F.	Tower Pressure mm Hg.
			Series 1	Series 2	Series 3	Series 4			
0.277	1558	126.64	98.65	96.82	97.73	97.89	97.77	91.0	746
	3116	126.64	108.10	107.24	109.03	108.08	108.11	89.5	746
	4674	126.64	110.64	112.67	110.55	112.58	111.61	89.1	746
	6232	126.64	115.22	112.34	112.63	113.46	113.41	88.8	746
0.412	1558	189.98	87.92	86.68	87.59	88.85	87.76	92.4	750
	3116	189.98	102.85	103.94	103.44	101.95	102.97	90.3	750
	4674	189.98	107.20	108.96	108.03	108.48	108.17	89.5	751
	6232	189.98	110.72	111.65	109.90	110.80	110.77	89.1	751

Ammonia Flow Lbs./hr.	Water Flow Lbs./hr.sq.ft.	Air Flow Lbs./hr.sq.ft.	Ml of NaOH for Back-Titration				Average Ml	°F. Temperature Water Out	Tower Pressure
			Series 1	Series 2	Series 3	Series 4			mm Hg.
0.552	1558	253.29	77.35	78.50	78.46	79.44	78.44	93.8	753
	3116	253.29	98.10	99.20	97.08	98.29	98.17	91.0	753
	4674	253.29	104.60	104.47	104.80	104.55	104.61	90.0	753
	6232	253.29	108.95	108 15	107.00	108 12	108.06	89.5	754
0.684	1558	316.62	72.00	70.12	71.00	71.09	71.05	94.9	760
	3116	316.62	94.40	92.35	95.22	91.24	93.30	91.7	760
	4674	316.62	101.31	101.15	101.29	101.12	101.22	90.5	760
	6232	316.62	106.50	105.36	104.55	105.62	105.51	89.9	761
0.821	1558	379.93	63.40	64.35	62.47	63.55	63.44	96.0	765
	3116	379.93	88.73	89.55	87.53	88.64	88.61	92.3	766
	4674	379.93	98.90	97 71	96.84	97.82	97.82	91.0	767
	6232	379.93	103.94	102.88	100.86	103.75	102.86	90.3	768
0.957	1558	443.27	54.15	55.13	56.22	55.25	56.19	97.1	773
	3116	443.27	83.95	82.91	81.82	86 99	83.92	93.0	774
	4674	443.27	95.27	96.35	93.41	92.50	94.38	91.5	775
	6232	443.27	102.12	99.20	99.31	100.41	100.26	90.7	781
1.096	1558	506.57	49.25	51.35	48.34	48.19	49.28	98.0	781
	3116	506.57	78.85	79.90	77.00	79 05	78.95	93.7	782
	4674	506.57	93.74	89.64	88.58	90.60	90.64	92.0	787
	6232	506.57	96.42	98.55	95.51	99.45	97.48	91.1	793
1.229	1558	569.91	41.91	40.85	43.99	41.10	41.96	99.1	789
	3116	569.91	74.10	75.88	73.05	72.92	73.99	94.4	791
	4674	569.91	85.20	88.10	89.07	86.23	87.15	92.5	805
	6232	569.91	94.73	92.90	97.83	93.85	94.83	91.4	810
1.365	1558	633 22	31.90	32.04	32.00	27.95	30.97	100.6	800
	3116	633.22	69.75	70.62	67 70	66.65	68.68	95.2	806
	4674	633.22	85.60	82.50	81.47	84.55	83.53	93.1	810
	6232	633.22	93.05	90.30	91.22	94.15	92.48	91.8	815

APPENDIX 5

GENERAL DATA

Solutions

The sodium hydroxide solution was prepared by dissolving sodium hydroxide in water. To standardize, the solution was titrated against a known quantity of benzoic acid.

Weight of Benzoic Acid Grams	Ml. of Sodium Hydroxide Solution	Normality of NaOH Solution
0.7022	11.80	0.4878
0.5126	8.60	0.4886

The average concentration was 0.4882 N NaOH.

The hydrochloric acid solution was prepared and titrated against the standard NaOH solution.

Ml. HCl Solution	Ml. of NaOH Solution	Normality of HCl Solution
25.00	29.70	0.5800
25.00	29.7	0.5800

The average concentration was 0.5800 N HCl.

Column Diameter

The inside diameter was 3.0 in. The cross-section area was calculated to be 0.0491 sq. ft.

APPENDIX 6

CALCULATION OF PRESSURE DROP

The pressure drop per foot of packing was determined by subtracting the pressure drop through the empty column from the pressure drop through the packed column for any specified air flow. This result was then divided by the height of the packing.

This correction was deemed necessary since the support and distribution plates in the column presented a large pressure drop.

Table 18 shows a sample set of calculations.

Table 18. Calculation of Pressure Drop per Foot of Packing

Air Flow Lbs./hr.sq.ft.	ΔP Empty Column	ΔP at 1225 Lbs.Water/hr.sq.ft.	Total ΔP Inches Water	ΔP/Ft. Inches Water/Ft.
63.32	0.67	0.73	0.06	0.013
126.64	2.49	2.70	0.21	0.047
189.98	5.35	5.80	0.45	0.10
253.29	9.22	10.08	0.86	0.19
316.62	14.20	15.51	1.31	0.29
379.93	19.95	21.66	1.71	0.38
443.27	26.90	29.65	2.75	0.61
506.57	34.70	38.57	3.87	0.86
596.91	43.00	48.40	5.40	1.20
633.22	53.00	60.20	7.20	1.60

APPENDIX 7

ABSORPTION CALCULATIONS

The molecular weight of ammonia is 17.032 lbs./mole.

The molecular weight of water is 18.016 lbs./mole.

The weight flow divided by the respective molecular weight and cross section area gives the molar flow rate per sq. ft.

$$\frac{0.277 \text{ lbs. ammonia/hr.}}{17.032 \text{ lbs./lb.mole}} \times \frac{1}{0.0491 \text{ sq.ft.}} = 0.331 \frac{\text{lb.moles ammonia}}{\text{hr.-sq.ft.}}$$

The molarity of the water effluent was calculated by the equation:

$$(\text{ml.HCl})(\text{normality HCl}) = (\text{ml.NaOH})(\text{normality NaOH}) + (\text{ml.effluent})\left(\frac{\text{molarity}}{\text{effluent}}\right)$$

$$100\ (0.5800) = 97.77(0.4882) + 50(\text{normality effluent})$$

$$\text{Molarity} = 0.2054 \text{ moles } NH_4OH/\text{Liter}$$

The molarity is converted to the mole ratio, mole ammonia per mole water as follows:

$$\frac{\text{Molarity}}{1000} \times \frac{\text{Molecular weight water}}{\text{Density of water effluent}}$$

$$= \frac{\text{gm.moles}}{\text{Liter}} \times \frac{\text{liter}}{1000 \text{ ml.}} \times \frac{18.016 \text{ gms.}}{\text{gm. mole}} \times \frac{\text{ml.}}{\text{gms.}}$$

$$= \frac{0.2054}{1000} \times \frac{18.016}{0.99498} = 0.00372 \frac{\text{moles } NH_3}{\text{mole water}}$$

The number of transfer units were calculated from the equation

$$N_{OG} = \frac{1}{\phi} \quad \frac{(Y_1-Y_2)}{(Y_1-Y_1^*)-(Y_2-Y_2^*)} \quad \ln \frac{(Y_1-Y_1^*)}{(Y_2-Y_2^*)}$$

where N_{OG} = total number of overall gas transfer units.

Y_1 = moles ammonia per mole air in inlet gas.

Y_2 = moles ammonia per mole air in outlet gas.

Y_1^* = moles ammonia per mole air in equilibrium with water outlet at concentration X_1 moles ammonia per mole water.

Y_2^* = moles ammonia per mole air in equilibrium with water inlet at concentration X_2 moles ammonia per mole water.

ϕ = correction factor.

$$= \frac{1}{2} \quad \frac{1}{1+Y_1} + \frac{1}{1+Y_2}$$

The value of Y_1 is set by experimental control. The value of Y_2 is obtained from the material balance equation,

$$Y_2 = Y_1 + \frac{L}{G} X_2 - \frac{L}{G} X_1$$

where X_2 = zero, Y_1 is controlled, and X_1 is determined by analysis as described above.

Y_2^* is the concentration of the gas stream in equilibrium with the inlet water. Therefore Y_2^* = zero.

Y_1^* is the concentration of the gas stream in equilibrium with the outlet water. To determine the value Y_1^* corresponding to a specific X_1 and total pressure it is necessary to construct an

equilibrium curve of gas composition versus liquid composition. This curve may take into account the temperature variation through the column. Using the data and formula in the International Critical Tables (27,28), the adiabatic temperature rise was calculated for each value of X between X_2 and X_1. The results are shown in Table 19.

Table 19. Temperature as a Function of Liquid Composition

X Moles Ammonia Per Mole Water	Temperature Rise (^{o}F.)	Temperature of Water (88'+ T)^{o}F.
0.002	1.6	89.6
0.004	3.3	91.3
0.006	4.9	92.9
0.008	6.5	94.5
0.010	8.2	96.2
0.012	9.8	97.8
0.014	11.4	99.4
0.016	13.0	101.0
0.018	14.6	102.6
0.020	16.1	104.1

Data of Sherwood (29) give the partial pressures of ammonia in equilibrium with liquid at various compositions and temperatures. By a simple straight line interpolation the partial pressures of ammonia in equilibrium with the liquid in the tower may be calculated. The results are shown in Table 20.

Table 20. Partial Pressure of Ammonia Over Liquid at Certain Compositions and Temperatures

X Moles Ammonia Per Mole Water	Temperature of Solution (°F.)	Partial Pressure of Ammonia for Solution at 104°F. (m.m.Hg.)	Partial Pressure of Ammonia for Liquid at 86°F. (m.m.Hg.)	Calculated Partial Pressure of Ammonia for Tower Solution
0.002	89.6	3.04	1.76	1.96
0.004	91.3	5.94	3.51	4.10
0.006	92.9	8.90	5.41	6.54
0.008	94.5	11.6	7.1	8.99
0.010	96.2	14.3	9.0	11.7
0.012	97.8	17.3	10.9	14.8
0.014	99.4	20.0	12.8	17.9
0.016	101.0	22.8	14.6	21.2
0.018	102.6	25.7	16.5	24.8
0.020	104.1	28.4	18.3	28.5

The value Y_1^* for any point is obtained from the formula

$$Y_1^* = \frac{\text{Partial pressure of ammonia}}{\text{Total pressure - partial pressure ammonia.}}$$

Therefore, an equilibrium curve of Y^* vs. X may be constructed for each total pressure found in the experiments. A typical calculation of N_{OG} then becomes

$$N_{OG} = \frac{(0.9295 + 0.9978)}{2} \frac{[(.07867)}{[(0.0707) - (0.0022)]} \ln \frac{(0.0707)}{(0.0022)}$$

$$= 3.87 \text{ overall transfer units}$$

Since the total height of the packing equals $N_{OG}\ H_{OG}$, and the packing

height for absorption was 2.0 feet, $H_{OG} = 2/N_{OG}$

$$= 0.52 \text{ feet.}$$

The absorption coefficient

$$K_G a = G_m / H_{OG} P$$

where $K_G a$ = lb.moles/hr.-cu.ft.-atm.

G_m = lb.moles air flow/hr.sq.ft.

P = tower pressure in atmospheres.

The results of these calculations are shown in Table 21.

APPENDIX 8

ABSORPTION RESULTS

Table 21. Absorption Coefficients for Moebius Rings in Air-Ammonia Water System

Liquid Flow Lb.Moles Water Per Hr. Per Sq.Ft.	Air Flow Lb.Moles Air/ Hr./ Sq.Ft.	Y_1	X_1	Y_2	Y_1*	N_{OG}	H_{OG}	K_Ga
86.5	4.37	0.07582	0.00372	0.0022	0.0051	3.87	0.52	8.55
173.0			0.00189	0.0010	0.0025	4.61	0.43	10.34
259.4			0.00127	0.0004	0.0017	5.54	0.36	12.35
345.9			0.000954	0.00025	0.0013	6.02	0.33	13.47
86.5	6.55	0.07527	0.00549	0.0028	0.0079	3.70	0.54	12.29
173.0			0.00280	0.0014	0.0038	4.29	0.47	14.12
259.4			0.00188	0.0008	0.0025	4.83	0.41	16.15
345.9			0.00142	0.00029	0.0019	5.89	0.34	19.48
86.5	8.73	0.07561	0.00714	0.0049	0.0107	3.16	0.63	13.99
173.0			0.00365	0.0033	0.0050	3.42	0.58	15.19
259.4			0.00251	0.0010	0.0033	4.65	0.43	20.49
345.9			0.00190	0.0003	0.0025	5.90	0.34	25.87
86.5	10.92	0.07499	0.00845	0.0081	0.0127	2.62	0.76	14.37
173.0			0.00451	0.0035	0.0062	3.38	0.59	18.51
259.4			0.00311	0.0011	0.0040	4.59	0.44	24.81
345.9			0.00235	0.0005	0.0030	5.37	0.37	29.45
86.5	13.10	0.07490	0.00980	0.0102	0.0152	2.41	0.83	15.67
173.0			0.00534	0.0044	0.0075	3.18	0.63	20.63
259.4			0.00371	0.0014	0.0049	4.34	0.46	28.20
345.9			0.00282	0.0004	0.0037	5.65	0.35	37.02
86.5	15.29	0.07484	0.01114	0.0118	0.0176	2.28	0.88	17.04
173.0			0.00617	0.0050	0.0087	3.06	0.65	23.07
259.4			0.00432	0.0015	0.0059	4.32	0.46	32.56
345.9			0.00328	0.0006	0.0043	5.25	0.38	39.14
86.5	17.47	0.07505	0.01231	0.0142	0.0142	2.11	0.95	17.89
173.0			0.00705	0.0053	0.0053	3.04	0.66	25.70
259.4			0.00498	0.0011	0.0011	4.72	0.42	40.13
345.9			0.00377	0.0004	0.0004	5.72	0.35	47.81

Liquid Flow Lb.Moles Water Per Hr. Per Sq.Ft.	Air Flow Lb.Moles Air/ Hr./ Sq.Ft.	Y_1	X_1	Y_2	Y_1	N_{OG}	H_{OG}	K_Ga
86.5	19.65	0.07485	0.01361	0.0150	0.0150	2.09	0.96	19.71
173.0			0.00793	0.0051	0.0051	3.13	0.64	29.48
259.4			0.00560	0.0010	0.0010	4.86	0.41	45.25
345.9			0.00424	0.0003	0.0003	6.08	0.33	55.86
86.5	21.84	0.07479	0.01556	0.0132	0.0132	2.36	0.85	24.40
173.0			0.00897	0.0037	0.0037	3.58	0.56	36.73
259.4			0.00624	0.0007	0.0007	5.36	0.37	55.35
345.9			0.00471	0.00017	0.00017	6.77	0.30	67.83

Units

Liquid Flow = lb.moles water/hr.sq.ft.

Air Flow = lb.moles air/hr.sq.ft.

Y_1, Y_2, Y_1* = moles ammonia/mole air

X_1 = moles ammonia/mole water

N_{OG} = number of overall transfer units

H_{OG} = height of overall transfer unit (feet)

K_Ga = lb.moles/hr.-cu.ft.-atm.

APPENDIX 9

HOLDUP DATA

Table 22. Liquid Holdup for Moebius Rings

L	h_o			$\frac{h_o}{\text{Average}}$	H_o
	Series 1	Series 2	Series 3		
900	191	187	195	191	0.0343
1,210	215	222	215	216	0.0388
2,934	324	337	330	330	0.0593
4,400	410	398	406	405	0.0728
5,860	481	475	485	480	0.0862
7,230	520	530	525	525	0.0943
8,790	590	605	605	600	0.1079
10,240	636	649	650	645	0.1160
W + D	90	89	86	88	0.0633

L = Water Flow; (lbs./hr.-sq.ft.)

h_o = Holdup; (ml. water)

H_o = Operating holdup; (cu.ft.water/cu.ft.tower)

W + D = Wet and drained. This gives the static holdup.

The diameter of the tower was 3.0 inches. The height of packed bed was 4.0 feet for all liquid flows. For the W + D determination the packed bed was 1.0 feet.

APPENDIX 10

COMPARISON OF HOLDUP DATA

Figure 37 shows the comparison of the operating holdup for one-half inch Berl saddles, Raschig rings, and Moebius rings. The data for saddles and Raschig rings were obtained from Leva (30). The operating holdup for moebius rings does not show unusual deviation from other reported data.

The general equation,

$$H_o = a\ (L/Dp)^n$$

fits the data well.

H_o = Operating holdup; (cu.ft.water/cu.ft.tower).

L = Liquid rate; (lbs./hr.-sq.ft.).

Dp = Equivalent spherical packing diameter; (inches).

a, n = Constants.

H_s = Static holdup; (cu.ft.water/cu.ft.tower).

Table 23 gives the values of the constants and the static holdup. The static holdup for Raschig rings and Berl saddles was obtained from Norman (31).

Table 23. Static Holdup and Constants for Operating Holdup for One-Half Inch Packing

Packing	Raschig Rings	Berl Saddles	Moebius Rings
Dp	0.696	0.636	0.727
a X 10^3	2.5	0.79	0.89
n	0.65	0.55	0.51
H_s	0.0325	0.0317	0.0633

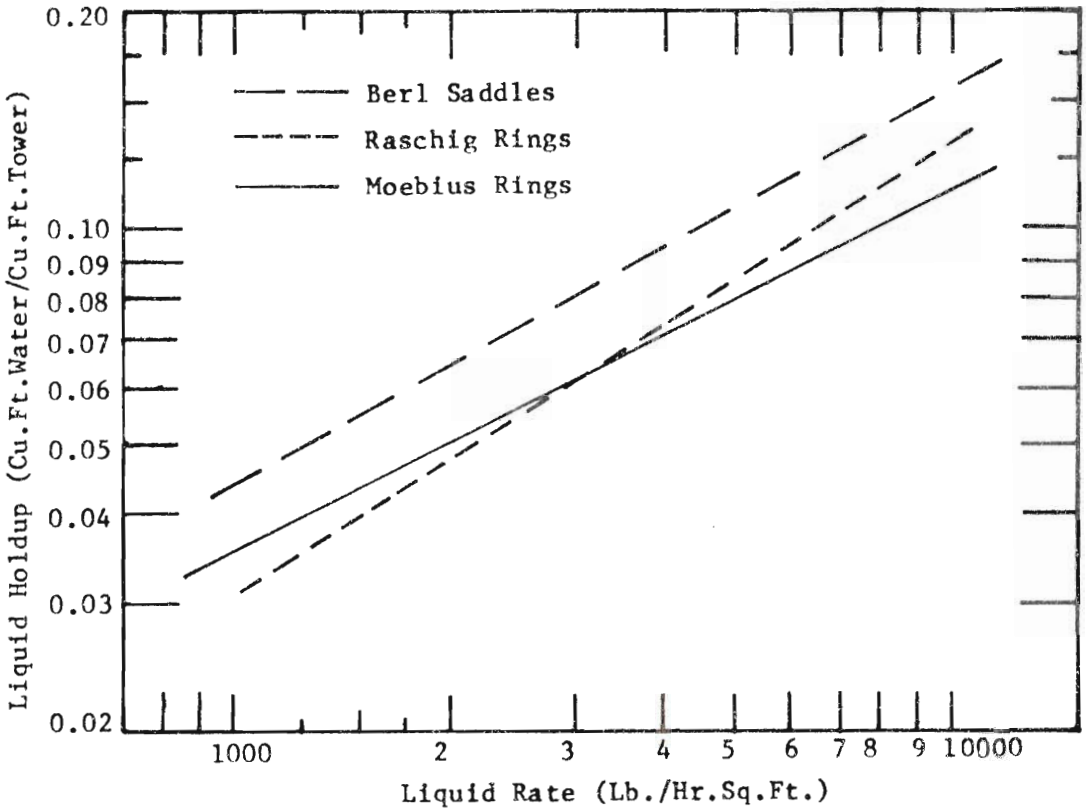


Figure 37. Holdup Data for One-Half Inch Packing

APPENDIX 11

THE CARMEN EQUATION

The pressure drop across a non-irrigated packing may be determined by means of the equation of Carmen (32). It has been shown that for spirals, spheres, and saddles,

$$\frac{\Delta p\, g_c\, \varepsilon^3}{Zd\, V_o^2\, a} = 5\,\frac{ma}{V_o d} + 0.4\left(\frac{ma}{V_o d}\right)^{0.1}$$

while for hollow spheres and certain rings that restrict flow through their internal passages,

$$\frac{\Delta p\, g_c\, \varepsilon^3}{Zd\, V_o^2\, a} = 5\,\frac{ma}{V_o d} + \left(\frac{ma}{V_o d}\right)^{0.1}$$

where

Δp = Pressure drop; (lb.-force/ft.^{2}).

Z = Depth of bed; (ft.).

g_c = Conversion constant; (32.2 lb.-mass.-ft./lb.force.sec.^{2}).

a = Area of particles/vol.of bed; (ft.^{2}/ft.^{3}).

d = Density; (lb.-mass/cu.ft.).

m = Viscosity; (lb.-mass/ft.-sec.)

V_o = Superficial velocity; (ft./sec.).

ε = Fraction of voids.

Table 24 shows the calculated pressure drops across non-irrigated moebius rings. From the correlation of these calculated pressure drops with those found by experiment, one may assume that the internal structure of the moebius ring does not hinder the gas flow when liquid is absent.

Table 24. Pressure Drops Across Moebius Rings Calculated from Carmen's Equation

Air Flow (Lb./hr.-sq.ft.)	Pressure Drop (Inches Water/Ft. Packing)
200	0.0405
300	0.0800
400	0.1338
500	0.2016
600	0.2851

When the packing is irrigated with water the pressure drop is increased. For liquid rates up to about 6000 lb./hr.-sq.ft., the effect on the pressure drop appears to depend primarily on the reduction in free space available to the gas (33). However, it is extremely difficult to predict reliable pressure drop information for various flow rates of gas and liquid from considerations of the proportion of the voids occupied by the two fluids (34). Many corrections must be taken into account. Two of these are the wall effect and the shape of the packing. Sherwood and Pigford (35) present an experimentally determined correction factor by which the pressure drop for a dry packing must be multiplied in order to

obtain the actual pressure drop for any rate of flow of water over Raschig rings and Berl saddles.

Figure 38 compares these correction factors with that determined for moebius rings.

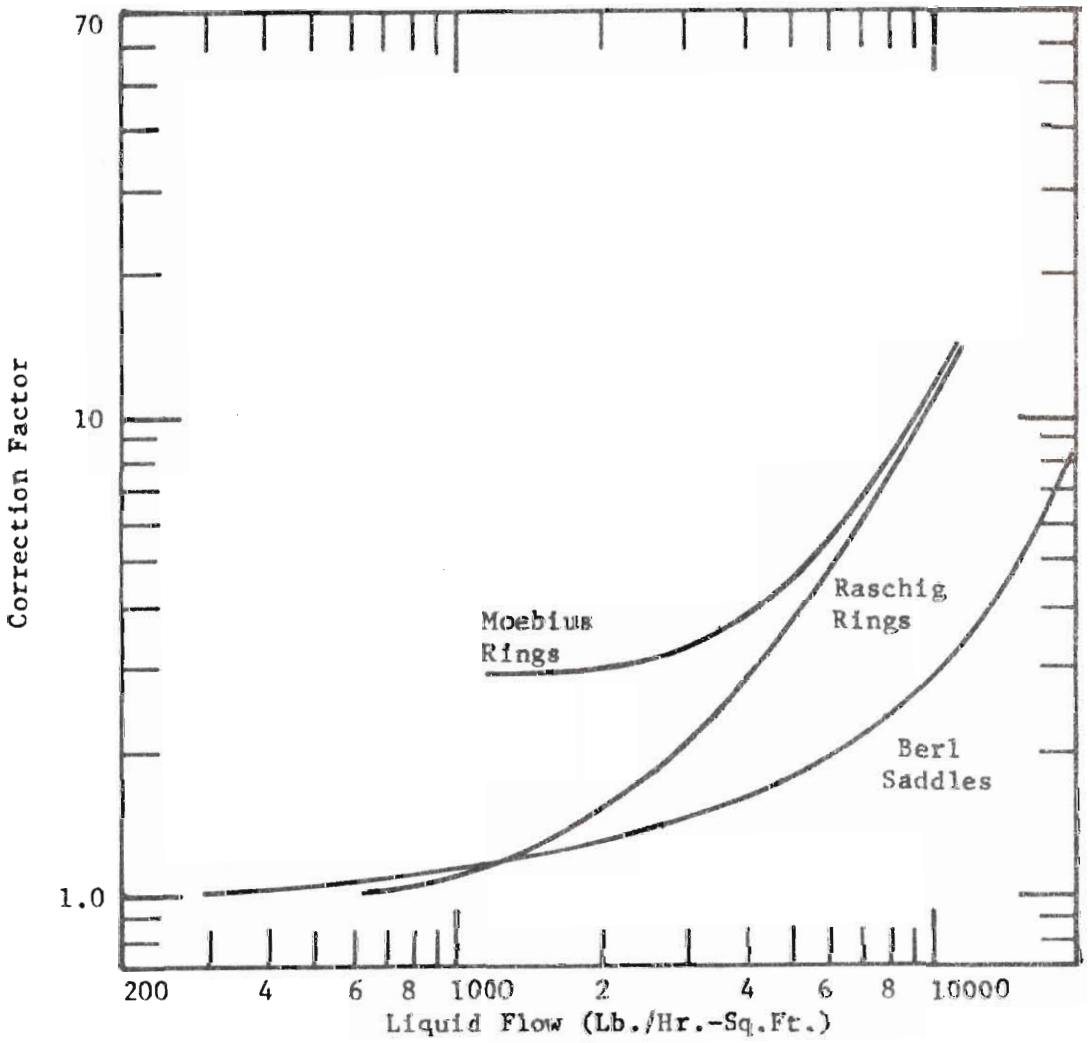


Figure 38. Effect of Liquid Rate on Pressure Drop for One-Half Inch Packing

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VITA

VITA

Zenon Redkevitch was born on June 16, 1930, in Montreal, Quebec. He received his elementary education in that city, completing high school in 1947. He entered the Massachusetts Institute of Technology in September of that year and was graduated cum laude in 1950 with the Bachelor of Science degree in chemistry. As an undergraduate he was a member of the Debating Society, the hockey team, the symphony orchestra, Phi Mu Delta and Kappa Kappa Sigma. He also received a partial tuition scholarship during his last two years at M.I.T.

After graduation he was employed as a Research Chemist with Dominion Tar and Chemical Company in Montreal. In 1951 he entered McGill University where he held a National Research Council Fellowship and a Teaching Fellowship in the Department of Chemistry. He was graduated in 1952 with the degree of Master of Science in Chemistry. He then entered the Georgia Institute of Technology and transferred into the School of Chemical Engineering in 1953. At Georgia Tech he held National Science Foundation Fellowship and a Rayonier Fellowship. During the years 1955 to 1958 he was a faculty member in the School of Mathematics.

He married Betty Jean Holliday in July, 1958, and they now have three children, two girls and one boy.

He is a member of several professional and honorary societies. These are Phi Lambda Upsilon, Sigma Xi, R.E.S.A., A.O.C.S., T.A.P.P.I.,

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